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ABSTRACT

This learning module aims to engage students in problem solving, critical thinking, scientific inquiry, and cooperative learning. The module is appropriate for use in any introductory or intermediate undergraduate course that focuses on human-environment relationships. The module examines the geography of human activities that produce the major greenhouse gases expected to cause global warming. The module teaches students about the basics of the global climate, energy balance, greenhouse effect, and the origins of regional and national emissions of the important greenhouse gases. It explores the many difficult issues involved in formulating and implementing global climate policy. The module concludes with a critical look at the international negotiations to reduce greenhouse gas emissions as required by the "United Nations Framework Convention on Climate Change." The module contains 7 tables, 8 figures, a list of acronyms, a guide, a summary, an overview, a glossary, references for all units, supporting materials, and appendixes (online sources, films, a guide to the UN Framework Convention, and selected readings). It is divided into thematically coherent; each of which consists of background information, teaching suggestions, student worksheets, and the answers expected for each activity. (Author/BT)

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# HANDS-ON!

# The Geography of Greenhouse Gas Emissions

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## An Active Learning Module on the Human Dimensions of Global Change

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HANDS-ON!

DEVELOPING ACTIVE
LEARNING MODULES ON THE
HUMAN DIMENSIONS OF GLOBAL CHANGE

# The Geography Of Greenhouse Gas Emissions

Module developed for the AAG/CCG2 Project
"Developing Active Learning Modules on the Human Dimensions of Global Change"

by

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Developing Active Learning Modules on the Human Dimensions of Global Change
"The Geography of Greenhouse Gas Emissions"

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# Editor's Note

A major goal of this project "Developing Active Learning Modules on the Human Dimensions of Global Change," is to disseminate instructional materials that actively engage students in problem solving, challenge them to think critically, invite students to participate in the process of scientific inquiry, and involve them in cooperative learning. The materials are appropriate for use in any introductory and intermediate undergraduate course that focuses on human-environment relationships.

We have designed this module so that instructors can adapt it to a wide range of student abilities and institutional settings. Because the module includes more student activities and more suggested readings than most instructors will have time to cover in their courses, instructors will need to select those readings and activities best suited to the local teaching conditions.

Many people in addition to the principle author have contributed to the development of this module. In addition to the project staff at Clark University, the participants in the 1995 summer workshop helped to make these materials accessible to students and faculty in a variety of settings. Their important contributions are recognized on the title page. This module is the result of a truly collaborative process, one that we hope will enable the widespread use of these materials in diverse undergraduate classrooms. We have already incorporated the feedback we have received from the instructors and students who have used this module, and we intend to continue revising and updating the materials.

I invite you to become part of this collaborative venture by sending your comments, reactions, and suggested revisions to us at Clark. To communicate with other instructors using hands-on modules, we invite you to join the Hands-on listserve we have established. We look forward to hearing from you and hope that you will enjoy using this module.

Susan Hanson
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# List of Acronyms

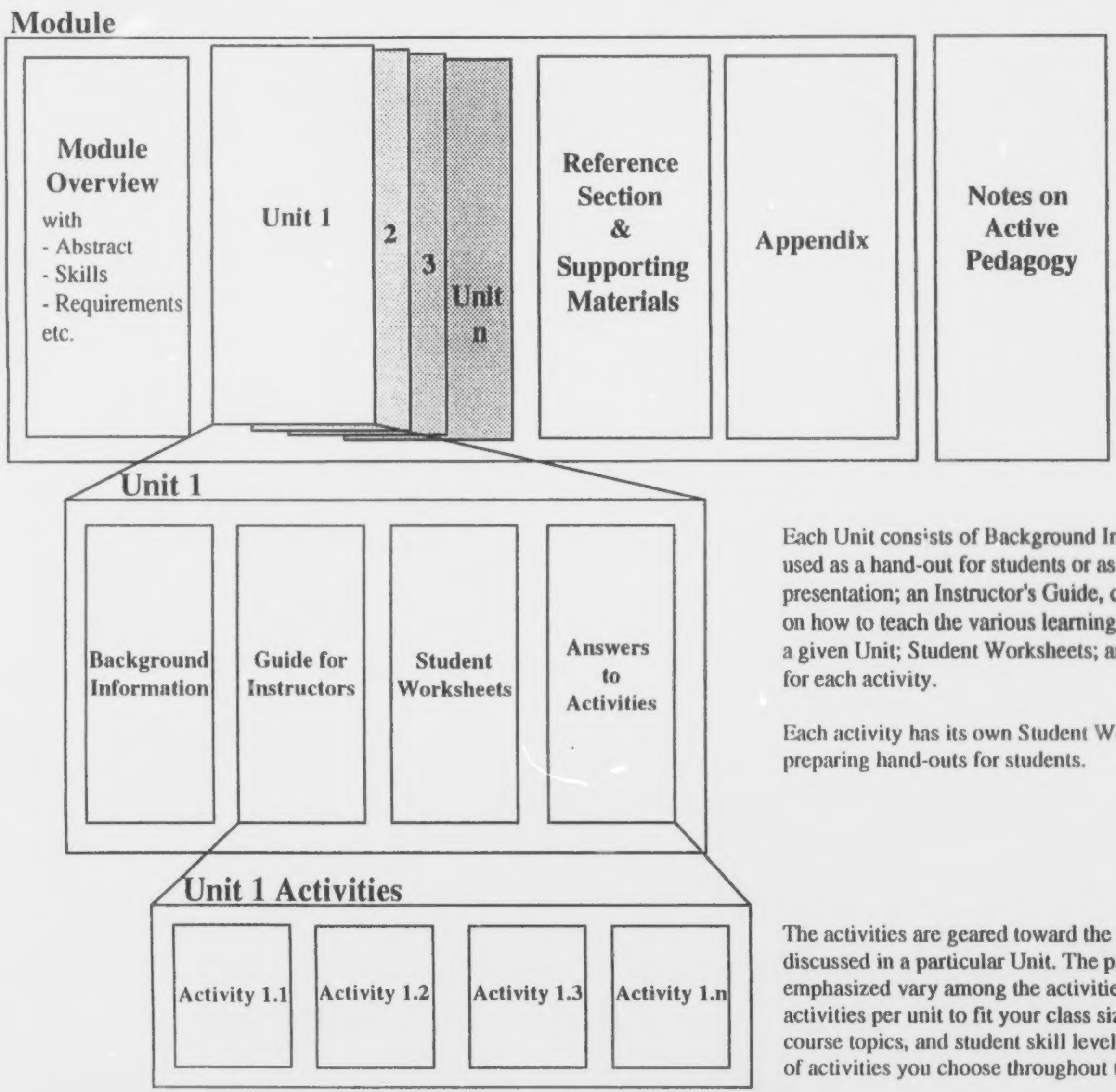
| | |
|---|---|
| **AOSIS** | Alliance of Small Island States |
| **COP** | Conference of Parties |
| **EEC** | European Economic Community |
| **EU** | European Union |
| **FCCC** | Framework Convention on Climate Change |
| **GEF** | Global Environmental Facility |
| **GFC** | Greenhouse Forcing Contribution |
| **GHG** | Greenhouse gases |
| **GMC** | General Circulation Model |
| **GNP** | Gross National Product |
| **GWP** | Global Warming Potential |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **INC** | Intergovernmental Negotiating Committee |
| **IU** | Investigative Unit |
| **IUCC** | Information Unit on Climate Change (UNEP/WMO) |
| **JI** | Joint Implementation |
| **MDB** | Multilateral Development Bank |
| **NGO** | Non-governmental Organization |
| **OECD** | Organization for Economic Cooperation and Development |
| **UNCED** | United Nations Conference on Environment and Development |
| **UNDP** | United Nations Development Program |
| **UNEP** | United Nations Environment Program |
| **WMO** | World Meteorological Organization |
| **WRI** | World Resources Institute |
| **WWF** | World Wildlife Fund |

## Other Abbreviations

| | |
|---|---|
| **CFC** | chlorofluorocarbons |
| **CO** | carbon monoxide |
| $CO_2$ | carbon dioxide |
| $CH_4$ | methane |
| **HC** | hydrocarbon |
| $H_20$ | water |
| $N_2O$ | nitrous oxide |
| $NO_X$ | nitrogen oxides |
| **OH** | hydrogen |
| $O_2$ | oxygen |
| $O_3$ | ozone |
| **ppm(v)** | parts per million (volume units) |
| **ppb(v)** | parts per billion (volume units) |
| $SO_2$ | sulfur dioxide |

# Guide to this Module

This guide is meant to help you navigate this module.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The module is divided into Units, i.e., sections that are thematically coherent and that could, if necessary, stand alone. In addition, the module contains a Reference Section, Supporting Materials and an Appendix. The Supporting Materials can be used to facilitate the teaching of this module or simply to augment it with interesting ideas and information. Additional sections with further information may or may not be present, e.g., a list of accronyms, or a glossary. A separate section on Active Pedagogy comes with every module purchase.

Each Unit consists of Background Information that can be used as a hand-out for students or as the basis for an in-class presentation; an Instructor's Guide, consisting of suggestions on how to teach the various learning activities associated with a given Unit; Student Worksheets; and the Answers expected for each activity.

Each activity has its own Student Worksheet for ease of preparing hand-outs for students.

The activities are geared toward the theme(s) and concepts discussed in a particular Unit. The particular skills and themes emphasized vary among the activities. Choose one or more activities per unit to fit your class size, time, resources, overall course topics, and student skill levels. Be sure to vary the types of activities you choose throughout the module.

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# Summary: The Geography of Greenhouse Gas Emissions

## Abstract

This module examines the geography of human activities that produce the major greenhouse gases expected to cause global warming. Students learn about the basics of the global climate, energy balance, greenhouse effect, and the origins of regional and national emissions of the important greenhouse gases. The will also learn to appreciate the many difficult issues involved in formulating and implementing global climate policy. The module concludes with a critical look at the international negotiations to reduce greenhouse gas emissions as required by the Framework Convention on Climate Change.

## Module Objectives

- Explain the basics of global warming and the role of different human activities in producing greenhouse gas emissions.
- Investigate national responsibilities for greenhouse gas emissions in the context of social driving forces such as development policies, population growth, and energy consumption using maps, graphs, and role-playing exercises.
- Understand the science and politics underlying the Framework Convention on Climate Change.

## Skills

- ✓ Choropleth mapping (by hand or using a computer package) and map interpretation
- ✓ Constructing and interpreting histograms, pie charts and scatterplots/XY-graphs
- ✓ Critical thinking, text and movie comprehension
- ✓ Role playing

## Activities

- ✓ Critical reading and thinking
- ✓ Map interpretation
- ✓ Choropleth mapping
- ✓ Keeping a personal energy log
- ✓ Role-playing
- ✓ Movies (*Only One Atmosphere* and
- ✓ *After the Warming -- Race to Save the Planet* series)
- ✓ Gopher/Web search (CDIAC, UNEP, Greenpeace)

## Material Requirements

- ✓ Readings and data tables (provided)
- ✓ Graph paper
- ✓ Regional outline maps (provided)
- ✓ Disk of World Resources Data (Approx. $100 from World Resources Institute) (optional)
- ✓ Computers with spreadsheet and choropleth mapping software (e.g., QuattroPro and AtlasGIS with world boundaries) and access to the internet/World Wide Web (optional)
- ✓ Movies (optional)

## Human Dimensions of Global Change Concepts

- ✓ Global warming/Global climate change
- ✓ Greenhouse gases
- ✓ Human driving forces
- ✓ International environmental policy

## Geography Concepts

- ✓ Energy balance climatology
- ✓ Human impact on the environment
- ✓ Regional population, consumption, and resource use

## Time Requirements

4-6 class periods

## Difficulty

Moderate. Students have to complete some basic math and analyze data tables and graphs. Critical text reading and discussion required.

## Module Overview

In 1988 the United Nations General Assembly established the Intergovernmental Panel on Climate Change (IPCC) to advise the world of the seriousness of global climate change. In 1990 the group published a report summarizing the conclusions reached by climate researchers from around the world: global climate change is a serious issue that requires immediate action.

The IPCC report states that human activities such as fossil fuel combustion and deforestation increase the amount of carbon dioxide ($CO_2$) in the Earth's atmosphere. Current consensus in the climate change scientific community predicts that even if $CO_2$ emissions were entirely eliminated today, the concentration of already-emitted greenhouse gases will lead to a significant warming of the Earth's atmosphere and cause many other climatic changes.

This module familiarizes students with the issues surrounding the IPCC; it addresses global climate change from two sides.

- First, students learn the climatological/physical fundamentals of global climate and the natural and anthropogenically enhanced greenhouse effect; students gain an understanding of the relevant processes and the involved radiated, active gases (Units 1 & 2). Students examine atmospheric changes over the past 250 years through close reading of text; interpreting charts, graphs, and tables; and data analysis.

- Second, students are introduced to the political and value-laden side of the global climate change problem (Units 3 & 4). At the Earth Summit in Rio in 1992 a number of nations signed the Framework Convention on Climate Change (FCCC), which has the goal of reducing greenhouse gas emissions and thus the risk of global warming. Each signing nation has prepared a climate action plan, which identifies the major sources of greenhouse gases and ways of reducing them. The Climate Convention faces many challenges, including scientific uncertainty about the impacts of global warming and a lack of information about patterns and trends in greenhouse gas emissions. There is political conflict regarding amounts of national emissions and the indices used to estimate responsibility, and countries vary in their willingness to act to reduce the risk of global warming. Students are asked to grapple with international policy making in the context of who bears responsibility for greenhouse gas emissions and in the context of the uncertainties surrounding the impacts of global warming.

This module provides students with sufficient technical knowledge to understand the debates surrounding global climate change and concludes with a section on personal actions and responsibility (Unit 5). The module activities include chart preparation and interpretation, short essay questions, role playing, mapping, and keeping a log of personal energy use.

# 1 Overview of the Global Warming Issue

## Background Information

Global warming is one of the global environmental changes that seems to have made it out of scientific research labs into the media, living rooms, coffeehouses, and classrooms. In other words, global warming is on the public and political agendas. In this introductory unit we will look at the scientific and political issues that underlie the global warming issue.

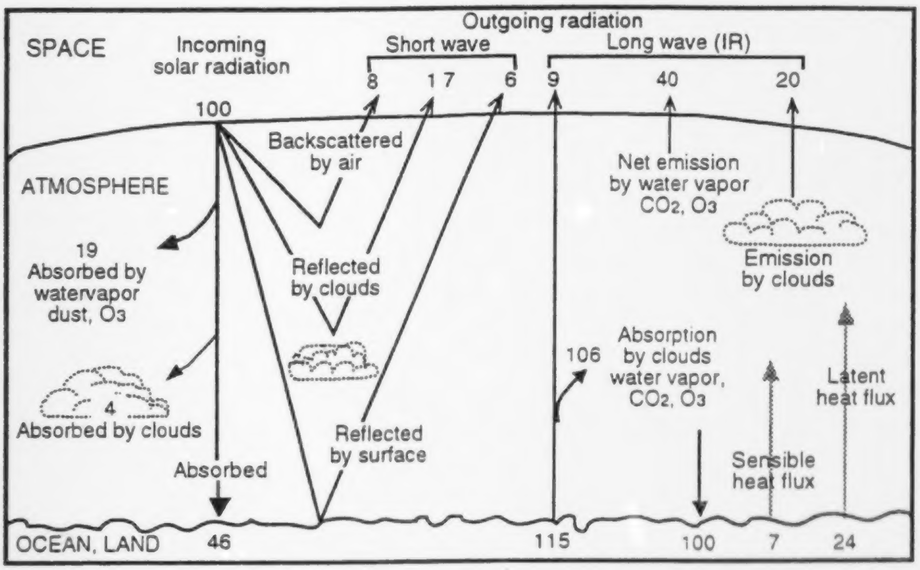
The cause of **global warming** is the increase in greenhouse gases in the atmosphere, especially carbon dioxide and methane, which trap **longwave (infrared) radiation** or heat that would normally be lost to space. These gases are increasing as a result of human activities. Fossil fuel consumption -- especially coal -- and deforestation produce carbon dioxide, the most important greenhouse gas. Cattle and rice production, landfills, and gas pipeline leaks produce another radiatively active gas: methane. The potential impacts of global warming include higher temperatures, changed rainfall patterns, storminess, and sea-level rise, all of which would alter agricultural production, natural ecosystems, and water resources, and would drown low-lying coastal areas.

While all of this sounds rather straightforward and unproblematic, the full scientific story behind global climate change is very complex and in many respects still poorly understood. Tremendous uncertainties and controversies surround the global warming issue.
The large majority of scientists, particularly the hundreds who participate in the **Intergovernmental Panel on Climate Change** (IPCC), believe that global warming poses a real threat that needs to be addressed. A few, however, remain skeptical; they believe that the world's climate is not fundamentally changing and that the efforts and resources exerted on the issue are misspent. Before we get into these uncertainties, complexities, and controversies let us first look at the climate fundamentals, so we better understand what the debates are about.

## The Global Energy Balance and Climate

Energy from the sun is the most important influence on climate. It is the motor that drives the Earth's climate. The amount of **shortwave (solar) radiation** entering the top of the **atmosphere** varies according to the time of day, the season of the year, and the latitude, with the greatest energy entering the atmosphere when the sun is directly overhead at midday in the summer in the tropics. The influx of shortwave energy into the atmosphere is balanced by longwave (thermal) energy that is reflected and radiated back into space. When the sun's energy enters the atmosphere, about 30% on average is **reflected** or scattered back into space by clouds, particles, and light colored land surfaces. Some of the energy is **absorbed** by clouds and particles in the atmosphere (20%), and the remainder is absorbed by the land surface, where it warms the environment or is used to evaporate water (which cools temperatures). The Earth's surface transfers this solar heat back to the atmosphere as longwave (infrared) radiation, through water evaporation and rising hot air (or thermals). Some of this outgoing energy from the surface is trapped by clouds and other substances in the atmosphere. The local balance between incoming shortwave and longwave radiation, reflected shortwave radiation, longwave reradiation, and energy transformed in the **evaporation** or **condensation** of water determines the temperature of the Earth's surface. Figure 1 below depicts this global energy balance schematically.

**Figure 1: Schematic Diagram of the Components of the Earth's Energy Balance**



SPACE
Incoming solar radiation
Outgoing radiation
Short wave
Long wave (IR)
8
17
6
9
40
20
100
Backscattered by air
ATMOSPHERE
Net emission by water vapor CO2, O3
Emission by clouds
19 Absorbed by watervapor dust, O3
Reflected by clouds
Absorption by clouds water vapor, CO2, O3
106
4 Absorbed by clouds
Reflected by surface
Latent heat flux
Sensible heat flux
Absorbed
OCEAN, LAND
46
115
100
7
24

The distribution of 100 units of incoming solar radiation and outgoing infared radiation on a global scale indicates excess heating at the Earth's surface. This excess heat is transferred to the atmosphere via sensible and latent heating.

Source: MacCracken. 1985. Carbon dioxide and climate change: Background and overview. In: *Projecting the climatic effects of increasing carbon dioxide*, eds. Michael C. MacCracken and Frederick M. Luther. DOE/ER-0237. Washington, DC: Department of Energy; his Figure 1.2 (p. 7).

What this short overview of the global energy balance shows is that the Earth's climate is the result of an intricate network of cycles, interactions, and **feedback loops** involving the atmosphere, oceans, ice-caps, living things, and even rocks and sediments (Leggett 1990: 15). Climate changes when the inputs or characteristics of the Earth system change. The most important causes of climate change are changes in the amount of solar energy at the top of the

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atmosphere, changes in the characteristics of the land surface, and changes in the composition of the atmosphere. The composition of the atmosphere will be of central importance in this module. All of these changes are brought about by the events and processes discussed in the following sections.

Solar input has varied with changes in the Earth's orbit around the sun, and with flares or spots in the sun itself (for a recent overview article see Lean and Rind 1996), possibly causing the ice ages. Heavy snowfalls in high latitudes can change land surface characteristics by creating snow and ice fields that will reflect much more sunlight than exposed land or water, and cause further local cooling of land surfaces. Over long periods of time the drifting of the continents altered the configuration of land and sea, with past warm or wet climates indicated by reserves of fossil fuels and the geological record. Volcanic eruptions, such as that of El Chichon in Mexico in 1984 or Mount Pinatubo in the Philippines in 1989, can throw veils of dust and sulfur gases high in the atmosphere, blocking sunlight, promoting cloud formation, and cooling the climate for several years.

## Human Impact on Climate

The possibility that human activity can significantly affect this Earth-climate system -- and how and how much -- lies at the root of the global warming debate. Although humans have no influence over the solar output of energy, they can change the characteristics of the land surface and alter the composition of the atmosphere. People have massively transformed the vegetation cover of the Earth through agriculture and deforestation. These changes in land use have affected local to regional climates. The persistent droughts in the Sahel during the 1970s, for example, were at least in part the result of overgrazing which increased the reflectivity of the Earth's surface, reducing surface warming and the turbulent rising of air that produces rain. One theory of the collapse of Mayan civilization in Central America suggests that deforestation for intensive agriculture dried the soils, reducing evaporative cooling and atmospheric humidity, leading to such intense desertification that farming was no longer possible (Gore 1992).

Local temperatures and rainfall have increased with the growth of cities because urbanization reduces the reflectivity and wetness of the land surface, and releases waste heat and pollutant particles to the atmosphere. There were fears that the oil wells put on fire in Kuwait during the Gulf War in 1991 would create a blanket of smoke that wouldn't permit the entry of sunlight, leading to colder temperatures. Even more dramatic are the scenarios of a "nuclear winter" which could be caused by the smoke and dust from multiple thermonuclear explosions in a global war.

Smoke and dust particles and debris from explosions are relatively short-lived residents in the atmosphere. Gaseous pollutants and greenhouse gas emissions in particular can have much longer residence times in the atmosphere and thus more severely affect the global energy balance.

## The Greenhouse Effect

The debate over our ability to affect the global climate centers on the so-called **greenhouse effect**, one of the most important mechanisms determining our planet's climate. In brief, the greenhouse effect is the natural warming control in our atmosphere. The atmosphere is mainly transparent to incoming shortwave radiation from the sun, but contains gases which trap the outgoing longwave energy, thereby warming the planet much like a blanket warms a person. This gaseous mass around the Earth, of course, does not have a glass ceiling, but with respect to temperature, it acts just like a greenhouse -- hence the name of this effect.

The greenhouse effect has been studied since the 1820s when a French scientist named Fourier described the phenomenon as a "hot house, because it lets through the light rays of the sun but retains the dark rays from the ground" (Nilsson 19XX: 6). The longwave radiation, Fourier's dark rays, is absorbed or trapped by greenhouse gases in the Earth's atmosphere, mainly water vapor and carbon dioxide ($CO_2$). Thus, most of the radiant heat emitted from the Earth's surface is trapped before it escapes from the atmosphere. This trapped radiant heat warms the Earth's surface some 33°C (the natural greenhouse effect), making it habitable for life as we know it.

The global average temperature has not been constant over the geologic history of our planet. In fact, over the last several decades, we have been able to learn a great deal about past climates from ice and ocean sediment cores. Trapped air bubbles in Antarctic ice cores have revealed information about past climates and changes in the composition of the atmosphere from 160,000 years ago to the present decade. The shells of plankton and other tiny organisms from the ocean floor give a measure of the temperature of the water when the shell was formed (Leggett 1990: 19; for a good overview of climate change over geologic time see Crowley 1996).

Studying these cores, researchers discovered that variations in the amount of atmospheric $CO_2$ closely correspond to variations in polar temperature. As the Earth moved in and out of glacial epochs, the amounts of atmospheric $CO_2$ and other greenhouse gases changed with the temperature, rising during interglacial periods and falling when glaciers were at their height. The ice cores indicate that increases in greenhouse gases were associated with the 5-7°C temperature swings between **glacial and interglacial periods** (IPCC 1990: xiv).

For the relatively recent past, say since the end of the last ice age over 12,000 years ago, global atmospheric carbon dioxide levels have been fairly stable at about 280 ppm for many hundreds of years. Before that -- about 120,000 years ago, the highest level of $CO_2$ reached during previous interglacial periods was 300 ppmv (IPCC 1990: 14). During the period 1000 to 1800 A.D., the atmospheric $CO_2$ concentration was between 270 and 290 ppmv. But as human populations have grown, and human activities and technologies have changed, we have changed the composition of the atmosphere. As we drive cars, heat our homes, manufacture products, and clear land for agriculture, we release large amounts of carbon dioxide and other gases into the atmosphere.

But more than the absolute amounts of emissions, we're interested in the concentrations of greenhouse gases since some of the gases released into the atmosphere are subsequently taken up by the oceans and the biosphere. And in fact, the data show that over the past 150 or so years, the concentration of greenhouse gases has significantly increased and they do so at ever increasing rates. What we generally see is that on a regional basis, the concentrations increase with the advent and advancement of industrialization. In Europe, this process began in the nineteenth century with the Industrial Revolution. In other regions it started later.

Many scientists believe that this increase in concentration enhances the natural greenhouse effect, upsetting the balance between incoming shortwave and outgoing longwave radiation and warming the Earth. By increasing the concentration of $CO_2$ and other greenhouse gases, we may be increasing the effectiveness of the atmospheric blanket, and allowing more of the heat radiating from Earth to be trapped by the atmosphere.

According to ice cores from Antarctica and direct atmospheric measurements at Mauna Loa, Hawaii, $CO_2$ concentrations reached a record high of 358 parts per million (ppm) in 1994 (WRI 1996). This level has not been observed anywhere in the measured ice core record during the past 160,000 years. Levels of the gas started to rise around 1800, increased by 15 ppmv by 1900, and had reached about 315 ppmv by 1958, when precise atmospheric measurements began (IPCC 1990: 12). Thus, since the Industrial Revolution, or about 1850, $CO_2$ has increased by about 28% as a result of human activity. The Intergovernmental Panel on Climate Change, an international group of science experts, stated in 1990 that if atmospheric greenhouse gases reach the equivalent of a doubling of $CO_2$, global temperatures will increase by 1.5°C to 4.5°C (with a best estimate of 3.0°C; this estimate was recently adjusted to about 2°C [IPCC 1995]). Although from a scientific viewpoint, we won't be absolutely sure of the enhanced greenhouse effect for another decade or so, evidence is accumulating that the enhanced greenhouse effect is in fact happening. For example, rising levels of greenhouse gases coincide with increasing global temperatures for the last century. The IPCC believes that the global mean surface air temperature has increased by 0.3°C to 0.6°C over the last 100 years, with the five warmest years occurring in the 1980s. After a few cooler years, caused by the sulfur dioxide emissions from the volcanic eruption of Mt. Pinatubo in the Philippines, 1995 was the most recent record-temperature year.

To place these temperatures into context, let's recall the temperature changes since the last ice age: the difference between the present Earth temperature and that of the last ice age about 12,000 years ago is approximately 5°C. Therefore, if the predictions are accurate, warming of the estimated magnitude will resemble that over the past 12,000 years and will result in major changes in climatic patterns and everything that depends on the climate (geophysical and biological processes). We should add that the warming since the last ice age occurred over thousands of years, whereas the currently predicted warming would take place in a matter of decades or centuries.

# 1 Overview of the Global Warming Issue

## Instructor's Guide to Activities

### Goal

The goal of Unit 1 activities is for students to identify greenhouse gases and learn the effects of greenhouse gases on the atmospheric energy balance. Students will also examine the historical trends in atmospheric concentrations of greenhouse gases.

### Learning Outcomes

After completing the activities associated with this unit, students should:

- understand the global energy balance
- understand the difference between the natural and human-induced greenhouse effects
- recognize the certainties and uncertainties associated with global warming
- be familiar with specific greenhouse gases and their atmospheric concentrations throughout history

### Choice of Activities

It is neither necessary nor feasible in most cases to complete all activities in each unit. Select activities that are most appropriate for your classroom setting and that cover a range of activity types, skills, genres of reading materials, writing assignments, and other activity outcomes. For this unit, the following activities are offered:

| | |
|---|---|
| 1.1 Climate in the Balance | --Text reading and short-answer worksheet |
| 1.2 So much fuss about so little gas | --Interpretation of graphs and tables; data analysis and short answer worksheet |

### Suggested Readings

The following readings are suggested to accompany the activities for this unit. Choose those readings most appropriate for the activities you select and those most adequate for the skill level of your students.

- Unit 1: Overview of the Global Warming Issue (provided)
  The background information to Unit 1 (all students should read)
- IPCC (Working Group I). 1990. *Scientific assessment of climate change: Executive summary*. Geneva, Switzerland: UNEP/WMO. (provided)
  This article accompanies Activity 1.1.

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## Activity 1.1 Climate in the Balance

### Goal

In this activity, students learn about the global energy balance and atmospheric greenhouse gases. They also learn the difference between the natural greenhouse and human-induced greenhouse effects.

### Skills

✓ critical thinking and text comprehension
✓ chart reading and interpretation

### Material Requirements

- Activity 1.1 Student Worksheet (provided)
- Suggested reading, IPPC (1990) (provided)

### Time Requirements

Activity 1.1 is suggested as a take-home assignment.

### Tasks

Students read the suggested reading and complete the Activity 1.1 Student Worksheet as homework.

## Activity 1.2 So Much Fuss About So Little Gas...

### Goal

The purpose of this activity is for students to understand the historical trends in atmospheric concentrations of greenhouse gases.

### Skills

✓ chart reading and interpretation
✓ simple math (percentage calculations)

### Material Requirements

- Activity 1.2 Student Worksheet (provided)
- calculator

### Time Requirements

1 class period (50 minutes)

### Tasks

Activity 1.2 is designed as an in-class assignment, building on Activity 1.1, in which students examine atmospheric changes over the past 250 years. Students will interpret figures, compute percentage changes, and answer the questions on the Student Worksheet. If you encounter math phobia during this activity, see the *Notes on Active Pedagogy* for helpful hints.

# 1

# Overview of the Global Warming Issue

## Student Worksheets

---

### Activity 1.1 Climate in the Balance

In this first activity we look at the global energy balance and those gases that contribute to the greenhouse effect. Read The IPCC Executive Summary (Scientific Assessment of Working Group I), then answer questions on this worksheet. Refer to Figure 2 on the following page to answer the first four questions.

---

A) How many of the 100 units of incoming solar radiation to our atmosphere are:

(i) scattered to space by the atmosphere and reflected to space by clouds and the surface?

(ii) absorbed by water vapor, dust, ozone, and clouds?

(iii) absorbed at the surface?

**B)** Of the 115 units of longwave energy emitted by the Earth's surface:

(i) how much is absorbed by clouds, water vapor, $CO_2$, and $O_3$?

(ii) how much escapes directly to space?

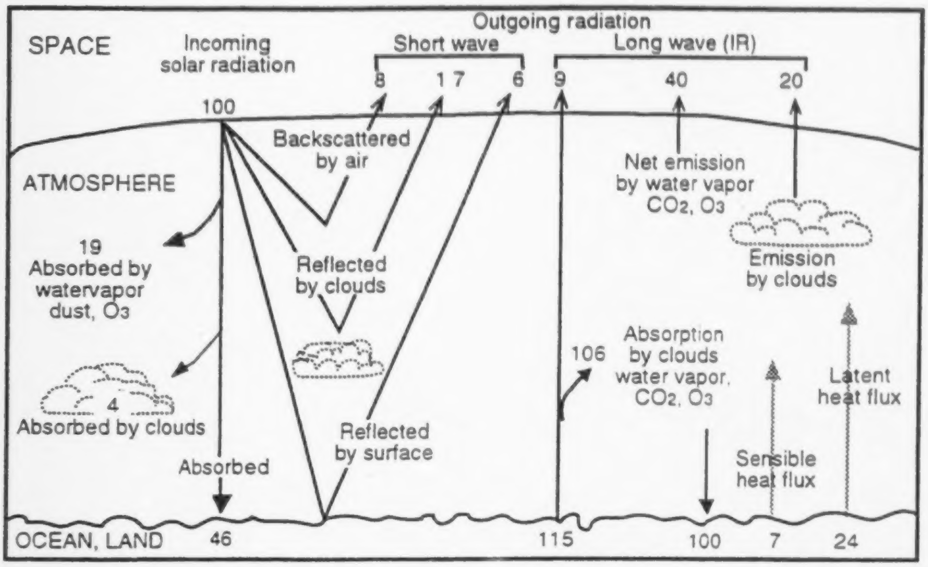
**C)** Describe the *natural* greenhouse effect in the context of the global energy balance.

**D)** Describe how human activity may be affecting the greenhouse effect in the context of the global energy balance.

**E)** According to the IPCC, what are three major areas of agreement and certainty about the greenhouse effect?

**F)** According to the IPCC, what are four major uncertainties about the greenhouse effect?

**Figure 2: Diagrammatic Representation of the Greenhouse Effect**


SPACE
Incoming solar radiation
100
Outgoing radiation
Short wave
8
17
6
Long wave (IR)
9
40
20
ATMOSPHERE
Backscattered by air
19 Absorbed by watervapor dust, O3
Reflected by clouds
4 Absorbed by clouds
Absorbed
Reflected by surface
Net emission by water vapor CO2, O3
Emission by clouds
106
Absorption by clouds water vapor, CO2, O3
Latent heat flux
Sensible heat flux
OCEAN, LAND
46
115
100
7
24

Source: MacCracken. 1985. Carbon dioxide and climate change: Background and overview. In: *Projecting the climatic effects of increasing carbon dioxide*, eds. Michael C. MacCracken and Frederick M. Luther. DOE/ER-0237. Washington, DC: Department of Energy; his Figure 1.2 (p. 7).

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## Student Worksheet 1.2 Name:

**Activity 1.2 So Much Fuss About So Little Gas...**

Atmospheric changes over the past 250 years have in recent years led to concern about global warming. Refer to Figures 3a-d and Figure 4 below to answer the following questions.

**A)** Rank the four greenhouse gases (GHGs) shown in Figure 3 by absolute atmospheric concentration for 1850.

1) 2) 3) 4)

**B)** Rank the four GHGs shown in Figure 3 by absolute atmospheric concentrations for 1991.

1) 2) 3) 4)

**C)** Using the formula provided below, calculate the percent change in the atmospheric concentration of GHGs from 1850 (the approximate beginning of the Industrial Revolution) to 1991 and enter your calculated values in the following table.

**Table 1: Atmospheric Concentration of GHGs**

| *GHG* | *1850 concentration* | *1991 concentration* | *Percent change* |
|---|---|---|---|
| $CO_2$ | 288 ppmv | 355 ppmv | |
| $CH_4$ | 700 ppbv | 1728 ppbv | |
| $N_2O$ | 280 ppbv | 306 ppbv | |
| CFC-11 | 0 ppbv | 0.272 ppbv | |

Source: Raven, P. H., *et al.* 1995. *Environment*. Fort Worth, TX: Saunders College Publishing.

Percent changes for each GHG can be calculated using the following formula:

$$\text{GHG percent change} = \left[\frac{1991\,concentration - 1850\,concentration}{1850\,concentration}\right] \times 100$$

$$\text{Example:} \quad CO_2 \text{ percent change} = \left.\frac{355-288}{288}\right] \times 100 = 23.3\%$$

Note: The calculation of the percentage change for CFC-11 presents you with a mathematical no-no! Division by zero is not allowed. You can easily see why: do the calculation several times with numbers very close to zero, e.g., 0.001, 0.0001, and 0.00001. What you will find is that the smaller the number in the denominator, the larger the result. So if in fact you divided anything by 0, you would end up with a result of positive infinitive. So, use 0.0001 to fill in the table -- you get the drift!

**D)** Now refer to the completed table above and rank the four GHGs from highest to lowest percent change in atmospheric concentration from 1850 to 1991.

1)  2)  3)  4)

**E)** So far we have looked at the concentrations of individual greenhouse gases. Now let's look at their relative contributions to the greenhouse effect. Figure 4 below presents the current relative contribution to projected global warming based upon computer model simulations. The relative contribution depends upon the atmospheric concentration and radiative effectiveness of each GHG. Rank the four GHGs based upon current relative contribution to global warming.

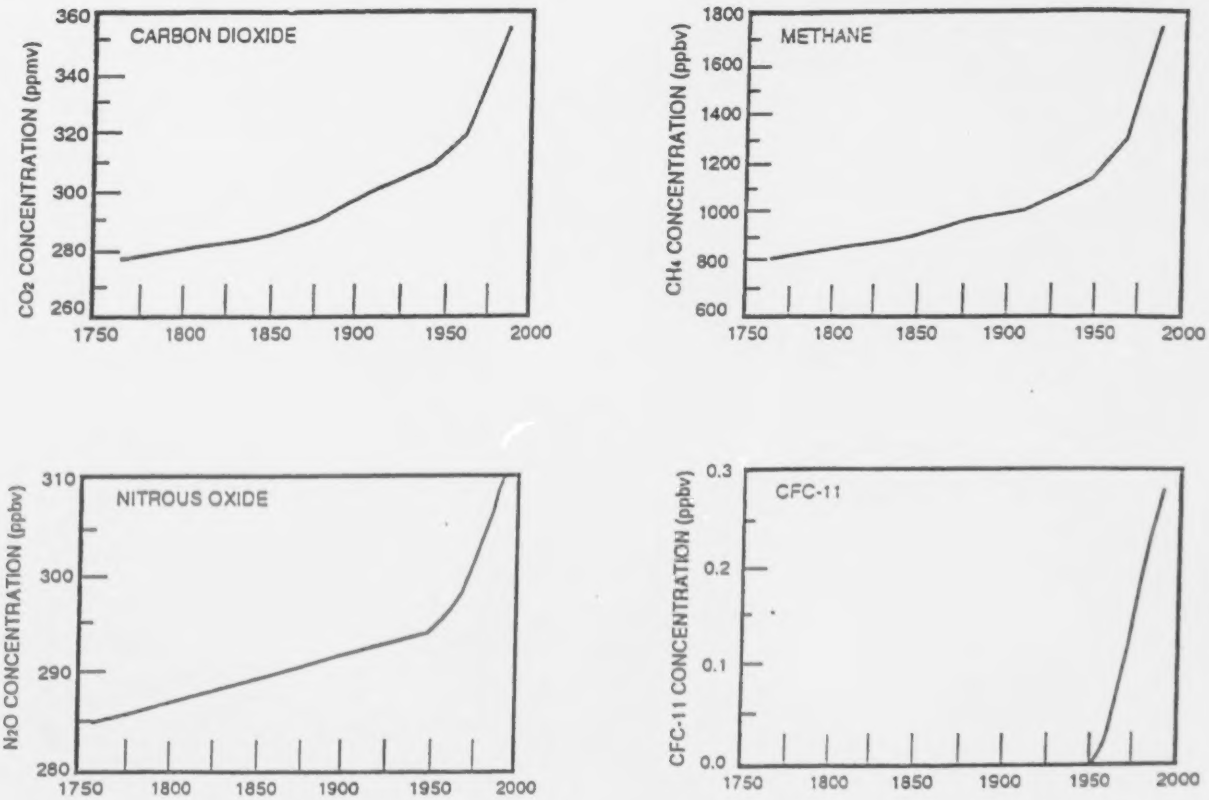
1)  2)  3)  4)

**F)** If you compare your answers to questions B, D, and E -- what do you notice? Given past trends and relative importance of each gas for the greenhouse effect, which GHGs should we be most worried about? Given the sources of these gases and what drives the increasing emissions (e.g., fossil fuel combustion, agriculture, deforestation) and the underlying forces of industrialization and population growth, how would you change or qualify your assessment of which gases are the big worry beads?

**G)** As we have seen, the atmospheric concentration of greenhouse gases has changed over time, and so has temperature. Examine the peaks and valleys in the local temperature change plot at the top of Figure 5 below. At first glance, what relationship do you detect between carbon dioxide, methane, and atmospheric temperature?

**H)** Now, using a 90° straight-edge (a piece of paper will do) line up the peaks and valleys of the temperature curve with the peaks and valleys of the GHG curves. Upon closer inspection, do the peaks and valleys in the methane curve lead, match, or lag the peaks and valleys in the temperature curve? How about $CO_2$? Why?

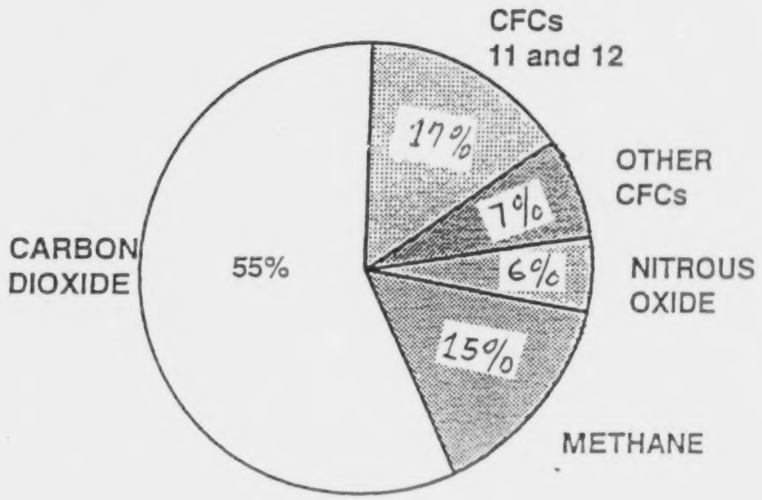
**Figure 3: Trends in Greenhouse Gas Atmospheric Concentrations Over the Past 250 Years: a) carbon dioxide - $CO_2$ (ppmv), b) methane - $CH_4$ (ppbv), c) nitrous oxide - $N_2O$ (ppbv), and d) chlorofluorocarbons - CFC-11 (ppbv)**



Concentrations of carbon dioxide and methane after remaining relatively constant up to the 18th century, have risen sharply since then due to man's activities. Concentrations of nitrous oxide have increased since the mid-18th century, especially in the last few decades. CFCs were not present in the atmosphere before the 1930s.

Source: IPCC. 1990. *Scientific assessment of climate change: Executive summary*. Geneva, Switzerland: UNEP/WMO; p.8., reprinted with permission.

Figure 4: Pie Graph of the Proportional Contributions of Human-Made Greenhouse Gases to Projected Global Warming for the Period 1980-1990 Based Upon Computer Model Simulations



The contibution from each of the human-made greenhouse gases to the change in radiative forcing from 1980 to 1990. The contribution from ozone may also be significant, but cannot be quantified at present.

Source: IPCC. 1990. *Scientific assessment of climate change: Executive summary*. Geneva, Switzerland: UNEP/WMO; adapted from their figure on p.11., reprinted with permission.

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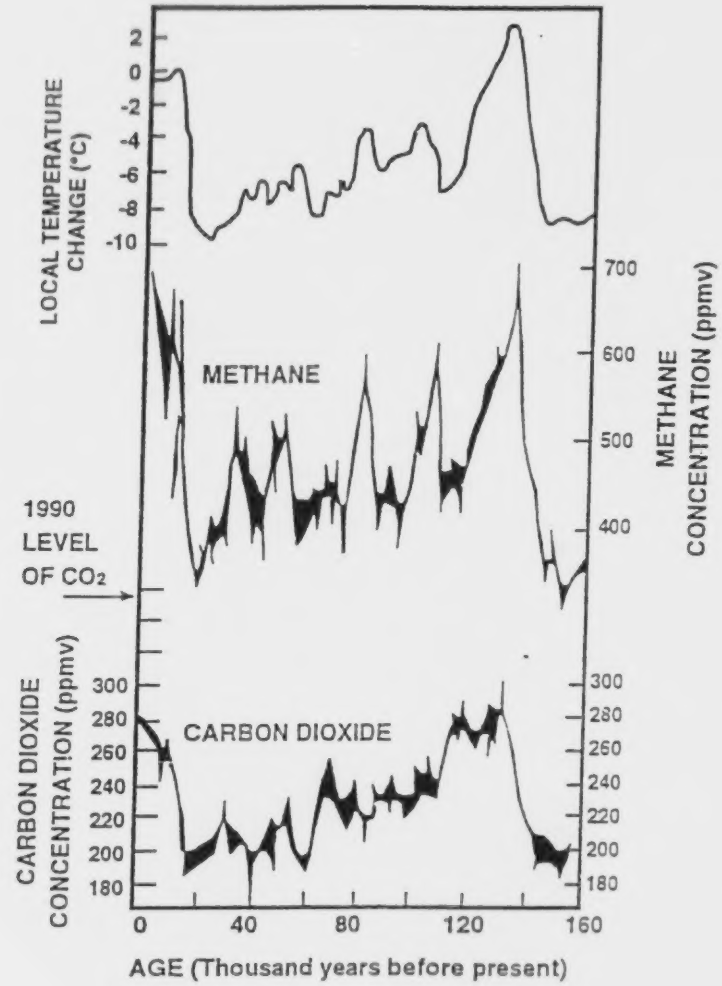
Figure 5: Carbon Dioxide, Methane, and Temperature Graphs



Analysis of air trapped in Antarctic ice cores shows that methane and carbon dioxide concentrations were closely correlated with the local temperature over the last 160,000 years. Present-day concentrations of carbon dioxide are indicated.

Source: IPCC. 1990. *Scientific assessment of climate change: Executive summary*. Geneva, Switzerland: UNEP/WMO; p.6, reprinted with permission.

# 1

# Overview of the Global Warming Issue

## Answers to Activities

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### Activity 1.1 Climate in the Balance

**A)** (i) scattered to space by the atmosphere and reflected to space by clouds and the surface
**31 units**
(ii) absorbed by water vapor, dust, ozone, and clouds
**23 units**
(iii) absorbed at the surface
**46 units**

**B)** (i) how much is absorbed by clouds, water vapor, $CO_2$, and $O_3$
**106 units**
(ii) how much escapes directly to space
**9 units**

**C)** Incoming solar (short wave) radiation from the sun is in balance with outgoing (long wave) radiation emitted by the earth's surface; however, not all of the long wave radiation from the earth's surface escapes into space. Earth's lower atmosphere continually absorbs long wave radiation emitted by the surface. This radiation is then re-emitted by the atmosphere back to the earth's surface, providing the planet with warmth. In this sense, the lower atmosphere acts like a greenhouse ceiling that returns heat energy to the earth surface.

**D)** Here, students should rely mostly on the readings. Humans increase the amounts of greenhouse gas concentrations in the atmosphere through the emission of carbon dioxide, nitrogen oxides, methane and other gases, thereby increasing the effectiveness of the atmosphere's absorption capabilities. This ultimately leads to an increase in the energy available to heat up global average atmospheric temperatures. However, many positive and negative feedback loops complicate this basic mechanism, such that it is as yet uncertain what the net effect on global temperatures will be.

**E)** According to the IPCC, what are three major areas of agreement and certainty about the greenhouse effect?

1. The greenhouse effect itself, both natural and anthropogenically enhanced, is well known and understood (IPCC, p.4-6). This includes a good understanding of the radiative potential and residence time of different gases.

2. The IPCC is certain about the natural and anthropogenically enhanced increases in greenhouse gas concentrations in the atmosphere, both over the earth's longer- and near-term history (IPCC, p.6-10). Furthermore, increases in greenhouse gas concentrations in the future are likely.
3. Which gases are crucial in producing the greenhouse effect is also known (IPCC, p.11).

**F)** According to the IPCC, what are four major uncertainties about the greenhouse effect?

1. The formation of clouds under an enhanced greenhouse effect and its feedback effects on global climate and temperature changes (IPCC, p.23).
2. The exchange of energy between oceans and the atmosphere, and within oceans, which control the rate and magnitude of global climate change (IPCC, p.24).
3. The quantification of greenhouse gases (emissions/sources, uptake, release) and how each of these processes is affected by an enhanced greenhouse effect (IPCC, p.24). Data problems like this are a ubiquitous problem in global change research.
4. The behavior of polar ice sheets which will affect predictions of sea-level rise (IPCC, p.24).

Generally, the greatest uncertainties surround the many positive and negative feedback effects that an altered unknown atmosphere and climate would have on processes that in turn affect the climate. These unknown feedback effects have trickle-down implications for many aspects: for example, the construction of General Circulation Models (GCMs)

- the results of models vary widely, especially for precipitation
- simplistic representations of oceans, ice, and clouds
- the resolution and topography of the models is too coarse
- models do not reproduce regional climates
- they do not provide us with good information about climate variability and extreme events;

furthermore, it is difficult to assess whether any warming has already occurred; climate changes for many reasons

- solar variability (sunspots, ice ages)
- surface characteristics (deforestation, urbanization)
- atmospheric composition (volcanic activity-Mount Pinatubo-sulfur pollution);

## Activity 1.2 So Much Fuss About So Little Gas...

**A)** Rank the four GHGs shown in Figure 3 by absolute atmospheric concentration for 1850.

1) **$CO_2$** 2) **$CH_4$** 3) **$N_2O$** 4) **CFC-11**

**B)** Rank the four GHGs by absolute atmospheric concentrations for 1991.

1) **$CO_2$** 2) **$CH_4$** 3) **$N_2O$** 4) **CFC-11**

**C)**

### Table 1: Atmospheric Concentration of GHGs

| *GHG* | *1850 concentration* | *1991 concentration* | *Percent change* |
|---|---|---|---|
| $CO_2$ | 288 ppmv | 355 ppmv | 23.3 |
| $CH_4$ | 700 ppbv | 1728 ppbv | 146.8 |
| $N_2O$ | 280 ppbv | 306 ppbv | 8.4 |
| CFC-11 | 0 ppbv | 0.272 ppbv | 27190* |

* As explained to students on the worksheet, this number will increase, the smaller the denominator they choose.

Note: The World Resources Institute's *World Resources 1996-97* offers figures for greenhouse gas concentrations for 1994. These values are listed below. They were not presented in the table above in order not to mix data sources.

| **1994 GHG concentrations:** | |
|---|---|
| $CO_2$ | 358.8 ppmv |
| $CH_4$ | 1666 ppbv |
| $N_20$ | 309 ppbv |
| CFC-11 | 0.261 ppbv |

Source: WRI. 1996. *World Resources 1996-97*. Washington, DC: WRI; their Table 14.3.

**D)** Rank the four GHGs from highest to lowest percent change in atmospheric concentration from 1850 to 1991.

1) **CFC-11** 2) **$CH_4$** 3) **$CO_2$** 4) **$N_2O$**

**E)** Rank the four GHGs based upon current relative contribution to global warming.

1) **$CO_2$** 2) **CFC-11** et al. 3) **$CH_4$** 4) **$N_2O$**

**F)** Which GHGs should we be most worried about? Why?

The following three rankings are to be compared:

1 -- absolute concentration: $CO_2$ - $CH_4$ - $N_2O$ - CFC-11
2 -- % change 1850-1990: CFC-11 - $CH_4$ - $CO_2$ - $N_2O$
3 -- relative contribution to greenhouse effect: $CO_2$ - CFC-11 - $CH_4$ - $N_2O$

Absolute concentrations by themselves really don't give much of a clue as to which gases are the biggest worry beads. In combination with the other rankings, however, we can derive at a clearer picture.

The radiative forcing potential of CFCs is demonstrated by their lowest absolute concentration but great contribution to the greenhouse effect. While CFCs have a very long residence time in the atmosphere, the Montreal Protocol is in place and in effect and will most likely over the next century lead to a slow decrease in the CFC concentration.

$CH_4$, while less powerful in its radiative forcing, ranks high in absolute concentrations and, most importantly, has increased tremendously over the recent past. Since its source is largely in agriculture (rice, livestock) which is likely to become more important as the world's population needs to be fed, $CH_4$ should be high on our worry list.

$N_2O$ weighs less on all counts but its source is linked to the major drivers behind greenhouse gas emissions: fossil fuel combustion and agriculture. It would therefore be imprudent to disregard the rising contributions of nitrogen oxides to the greenhouse effect.

$CO_2$ as the benchmark greenhouse gas is of greatest importance, both in absolute and relative terms; its lower ranking on the % change question hides the tremendous increase over this short period of time compared to its relative stability over previous centuries and millennia. Given the driving forces behind $CO_2$ emissions and the likely future prospects of population growth and industrialization in China, India, and many Third World countries, carbon dioxide continues to be our biggest worry bead.

**G) What relationship do you detect between carbon dioxide, methane, and atmospheric temperature?**

There appears to be a close correlation between the temperature curve on the one hand, and the GHG concentrations on the other.

**H) Upon closer inspection, do the peaks and valleys in the methane curve lead, match, or lag the peaks and valleys in the temperature curve? How about $CO_2$? Why?**

The largest peaks definitely do not coincide perfectly. There appears to be a time gap between highs and lows in the GHG concentrations and temperature (sometimes temperature precedes, at other times follows the GHG peaks/lows). In addition, there is not always a correspondence between high and low concentrations of methane and carbon dioxide as the general tendency suggest.

# 2 Greenhouse Gases

## Background Information

The most important greenhouse gases are water vapor[1] ($H_2O$), **carbon dioxide** ($CO_2$), **methane** ($CH_4$), **chlorofluorocarbons** (CFCs), **ozone** ($O_3$), and **nitrous oxide** ($N_2O$). The contribution of these gases to global warming depends on the amounts emitted to and removed from the air; the amount of time they remain in the atmosphere, their **residence time**; and their effectiveness in trapping longwave radiation, i.e., their **radiative potential.** Simply stated, the extent of the greenhouse effect is a function of the concentration of gases and the mix of gases in the atmosphere. The concentration of gases is the result of what is added minus what is removed per unit volume. The degree of warming also depends on a large number of other interacting variables such as cloudiness, soil moisture, counteracting pollutants such as **sulfur dioxide** and dust, ocean and land surface conditions. Below, we discuss the most important greenhouse gases in turn, and then look at the sources of each.

## The Greenhouse Gases

### Carbon dioxide

$CO_2$ is responsible for about 60 percent of the greenhouse warming. Its atmospheric concentration has increased tremendously since the Industrial Revolution (World Resources Institute 1994: 207). Humans release the gas into the **atmosphere** largely through **fossil fuel** burning and changes in land use such as deforestation. The carbon containing fuels include oil, coal, gas and wood. Land use conversion encompasses land changes like timber harvesting, and the clearing of forests or grasslands for cropland or pasture.

The global input of $CO_2$ to the atmosphere from fossil fuel combustion, plus minor industrial sources like cement production, has increased exponentially since 1860, about 4% a year though there were interruptions during the world wars, the economic depression of the 1930s, the "energy crisis" of the 1970s, and the collapse of the Soviet and Eastern European economies in the early 1990s.

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[1] Water vapor is not discussed any further in this unit; but its high effectiveness as a greenhouse gas and its uncertain amount in future atmospheric composition add to the uncertainty around global climate change predictions.

Deforestation since 1890 has greatly contributed to the total release of carbon. Although the greatest deforestation-related releases of carbon in the 19th and early 20th centuries were from temperate zone lands, the major source of carbon from deforestation during the past several decades has been from the tropics, with a significant increase since 1950. Some estimates put deforestation at about 23% of the total anthropogenic (human made) contribution of $CO_2$ (Leggett 1990: 17).

Fortunately, not all of the carbon dioxide emitted has remained in the atmosphere but has been taken up by the oceans and photosynthetic organisms such as green plants and algae. Still, scientists monitoring atmospheric $CO_2$ believe that almost half of all carbon emissions remain in the atmosphere.

**Carbon** has a natural **cycle** on Earth; it is emitted into the atmosphere by volcanoes and sea floor vents and absorbed by plants during photosynthesis. The carbon is stored in tree trunks and other living material and in plant debris in the soil. The gas is also absorbed by the atmosphere and by coral and other living organisms in the ocean. The oceans, plants, soils, and sedimentary rocks that "take up" $CO_2$ are referred to as **carbon sinks**. The most long-lasting storage component in this cycle are rocks such as limestone that contain high amounts of carbon..

This natural cycle is complex and long-lived, and many uncertainties exist concerning the balance of $CO_2$ in the oceans, atmosphere, and living matter in relation to the increase in atmospheric $CO_2$ resulting from human activity. Scientific field observations indicate that the oceans take up about half the carbon, but it is as yet unclear where the rest of it goes. That is the question of the so-called **missing sink** (World Resources Institute 1994: 207). Some scientists assume that the carbon is absorbed by an increasing growth of plants, but no one knows how and where the carbon is stored for certain, and it is very difficult to confirm increases in biomass on this order (IPCC 1990: 17).

It takes 50 to 200 years for atmospheric $CO_2$ to adjust to changes in sources or sinks, so that even if we halted all $CO_2$ emissions tomorrow, $CO_2$ would not return to preindustrial levels for hundreds of years. In fact, it may well be that $CO_2$ concentrations will never return to pre-industrial levels. The atmospheric lifetime (**residence time**) of a particle of $CO_2$ is estimated at about 100 years (IPCC 1990). Carbon dioxide is very effective in trapping **longwave radiation** and thus has a relatively high **radiative potential**.

## Chlorofluorocarbons (CFCs)

CFCs have been shown to deplete atmospheric ozone as well as to affect the Earth's radiative balance. Most CFCs are exclusively human-made; they are used in aerosol propellants, refrigerants, foam blowing agents, and fire retardants. These greenhouse gases have increased at rates of more than 4% a year for the past few decades, faster than any other greenhouse gas, and have atmospheric lifetimes of more than 50 years. As mentioned above, CFCs destroy ozone, which itself is another greenhouse gas, and it is unclear, as a result, whether CFCs have a net warming or cooling effect.

Because CFCs have also been implicated in the destruction of the **stratospheric ozone** layer and therefore in the resulting health risks of cancer, cataracts, and damage to plant and genetic material, the international community has agreed to control the use of CFCs. The Montreal Protocol on Substances that Deplete the Ozone Layer (1989), which has been signed by many countries, aims to reduce the use of CFCs greatly. Because of the long residence time of CFCs, significant atmospheric concentrations will remain for at least the next century (IPCC 1990: 25). There is reason to assume that CFC substitutes, such as halons, also act as greenhouse gases.

## Methane

Methane ($CH_4$) is produced naturally through anaerobic (oxygen-void) processes like those occurring in swamps and bogs during the decomposition of plant material. While this remains the major source of atmospheric methane, human activities such as growing rice in paddies, burning vegetation, raising livestock, and mining coal have increased methane levels to more than double preindustrial estimates, and methane levels are increasing about 1% a year (IPPC 1990: 22). There is also concern that global warming will melt current permafrost regions of the world thereby enlarging the area in which $CH_4$-producing processes occur naturally. Thus, increases of temperatures in high-latitude regions would function as a positive feedback to methane releases into the atmosphere, further enhancing global warming.

Methane reacts with OH (hydrogen) in the atmosphere resulting in a relatively short atmospheric residence time of about ten years. In order to stabilize concentrations at current levels, it is estimated that we would have to reduce our emissions by 15-20%.

## Nitrous oxide

$N_2O$ is one member of the family of nitrous oxides, which is collectively abbreviated as $NO_x$. We will focus only on $N_2O$ in this module since it is the nitrous oxide that is most important in terms of **radiative potential.**[3] The atmospheric concentration of nitrous oxide ($N_2O$) has increased 8% since pre-industrial times. Human sources for $N_2O$ include fossil fuel combustion, the burning of forests, and the use of nitrogen fertilizers. This gas is naturally produced in soils, but researchers have yet to determine the respective amounts of natural and anthropogenic sources of $N_2O$. It is believed, however, that the observed increase in concentrations is caused by human activities. Nitrous oxide is a particularly dangerous greenhouse gas because it both effectively absorbs longwave radiation coming from the Earth and has a very long atmospheric residence time, about 150 years.

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[3] $N_2O$ is the most powerful of all nitrogen oxides in forcing global warming.

# Important Anthropogenic Sources of Greenhouse Gases

## Energy Production & Consumption

The energy sector is the biggest contributor to human-induced climate change. Energy use is responsible for about three-quarters of humankind's carbon dioxide emissions, one-fifth of the methane ($CH_4$) we produce, and a significant quantity of our nitrous oxide emissions. It also produces other nitrogen oxides, hydro-carbons (HCs), and carbon monoxide (CO), which, though less important as **greenhouse gases** themselves, influence chemical cycles in the atmosphere that produce or destroy GHGs such as **tropospheric ozone**.

Most GHGs are released during the burning of fossil fuels. Oil, coal, and natural gas supply the energy needed to run automobiles, heat houses, and power factories. In addition to energy, however, these fuels also produce various by-products. Carbon and hydrogen in the burning fuel combine with oxygen ($O_2$) in the atmosphere to yield heat (which can be converted into other forms of useful energy) as well as water vapor and carbon dioxide. If fuel were to burn completely, the only by-product containing carbon would be carbon dioxide. Because combustion is often incomplete, however, other carbon-containing gases are also produced, including carbon monoxide, methane, and other hydrocarbons. In addition, nitrous oxide and other nitrogen oxides are produced as by-products when fuel combustion causes nitrogen from fuel or the air to combine with oxygen. Increases in tropospheric ozone are indirectly caused by fuel combustion as a result of reactions between pollutants caused by combustion and other gases in the atmosphere.

Extracting, processing, transporting, and distributing fossil fuels can also release greenhouse gases. These releases can be deliberate, as when natural gas is flared or vented from oil wells, emitting mostly methane or carbon dioxide, respectively. Other releases result from accidents, poor maintenance, or small leaks in well heads and pipe fittings. Methane, which appears naturally in coal seams as pockets of gas is "dissolved" in the coal itself, is released when coal is mined or pulverized. Methane, hydrocarbons, and nitrogen oxides are emitted when oil and natural gas are refined into end products and when coal is processed (which involves crushing and washing) to remove ash, sulfur, and other impurities. Methane and smaller quantities of carbon dioxide and hydrocarbons are released from leaks in natural gas pipelines. Hydrocarbons are also released during the transport and distribution of liquid fuels in the form of oil spills from tanker ships, small losses during the routine fueling of motor vehicles.

Some fuels produce more carbon dioxide per unit of energy than others. The amount of carbon dioxide emitted per unit of energy depends on the fuel's carbon and energy content. Coal emits about 1.7 times as much carbon per unit of energy when burned as does natural gas and 1.25 times as much as oil.

Although burning wood (and other biomass) produces a large amount of carbon dioxide, wood burning now contributes less to climate change than does burning fossil fuel because fossil fuels have replaced wood as the major energy source of industrialized societies. Wood, however, appears to have the highest **emission coefficient**, i.e., it releases more emissions of greenhouse gases and other pollutants per unit energy produced than other fuels. It should also be noted that the carbon contained in fossil fuels has been stored in the Earth for hundreds of millions of years and is now being rapidly released over mere decades. Carbon stored in plants has a much more rapid and quantitatively smaller cycle. When plants are burned as fuel, their carbon is recycled back into the atmosphere at roughly the same rate at which it was removed, thus making no net contribution to the pool of carbon dioxide in the air. The main problem with diminishing biomass in terms of the greenhouse effect lies in the destruction of carbon sinks.

It is difficult to make precise calculations of the energy sector's greenhouse gas emissions. Estimates of greenhouse gas emissions depend on the accuracy of the available energy statistics and on estimates of "emission factors," which attempt to describe how much of a gas is emitted per unit of fuel burned. Emission factors for carbon dioxide are well known, and the level of uncertainty in national $CO_2$ emissions estimates is thus fairly low, probably around 10%. For the other gases, however, the emission factors are not so well known, and estimates of national emissions may deviate from reality by a factor of two or more. Estimates of emissions from extracting, processing, transport, and so on are similarly uncertain.

## Land Cover Conversions

When biomass is removed *and* is not allowed to grow back -- as in the case of massive deforestation for agriculture -- the burning of biomass fuels can yield net carbon dioxide emissions. In that case deforestation leads to a loss of $CO_2$ sinks, a term that describes the part of the carbon cycle that takes up and stores $CO_2$ (like a growing forest for example) rather than releasing it.[4] (For a detailed discussion of the effects of $CO_2$ on forests and of forests on $CO_2$ concentrations see Trexler and Haugen 1994; Shands and Hoffman 1987; Brown et al. 1980; and Armentano and Jett 1980.)

Water-logging of fields, grass, or woodlands is another type of land cover conversion that leads to the release of greenhouse gases, specifically methane. Examples include rice cultivation (see below), or flooding of previously dry land by damming a river for electricity production. The reverse, drainage of flooded areas or wetlands, also affects greenhouse gas releases. When soils fall dry, soil processes adjust to the new aerobic (oxygen-rich) regime, increasing their release of $CO_2$.

## Methane from Livestock

About one-quarter of the methane emissions caused by human activities come from domesticated animals. The second-most important greenhouse gas after carbon dioxide, methane is released in the digestive processes of cattle, dairy cows, buffalo, goats, sheep, camels, pigs, and horses. It is also emitted by the wastes of these and other animals. Total annual methane emissions from domesticated animals are thought to be about 100 million tons. Animals produce methane through **"enteric fermentation,"** a process in which plant matter is converted by bacteria and other microbes in the animal's digestive tract into nutrients such as sugars and organic acids.

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[4] Conversely, reforestation or aforestation as a land cover conversion may help reduce atmospheric $CO_2$ concentrations.

These nutrients are used by the animal for energy and growth. A number of by-products, including methane, are also produced, but they are not used by the animal; some are released as gas into the atmosphere.

Microbial metabolism : Plant Organic Matter + $H_2O \longrightarrow CO_2 + CH_4$ + nutrients and other products

The amount of methane that an individual animal produces depends on many factors. The key variables are the species, the animal's age and weight, its health and living conditions, and the type of feed it eats. **Ruminants** -- such as cows, sheep, buffalo, and goats -- have the highest methane emissions per unit of energy in their feed, but emissions from some non-ruminant animals, such as horses and pigs, are also significant. National differences in animal farming are particularly important: for example, dairy cows in developing nations produce about 35 kg of methane per head year, while those in industrialized nations, where cows are typically fed a richer diet and are physically confined, produce about 2.5 times as much per head.

There is a strong link between human diet and methane emissions from livestock. For example, nations where beef forms a large part of the diet tend to have large herds of cattle. As beef consumption rises or falls, the number of livestock will, in general, also rise or fall, as will the related methane emissions. Similarly, the consumption of dairy goods, pork, mutton, and other meats, as well as of non-food items such as wool and draft labor (by oxen, camels, and horses), also influences the size of herds and methane emissions. Because of their large numbers, cattle and dairy cows produce the bulk of total emissions. Certain regions -- both developing and industrialized -- produce significant percentages of the global total. For example, emissions in South and East Asia are high principally because of large human populations; emissions per capita are slightly lower than the world average. Latin America has the highest regional emissions per capita primarily because of large cattle populations in the beef-exporting countries (notably Brazil and Argentina). Centrally planned Asia (mainly China) has by far the lowest per capita emissions because of a diet low in meat and dairy products.

## Methane from Rice Cultivation

Rice fields produce about 60 million tons of methane per year. This represents about 17% of total methane emissions resulting from human activities. Virtually all of this methane comes from "wetland" rice farming. Rice can be produced either by **wetland, paddy rice farming** or by **upland, dry rice farming**. Wetland rice is grown in fields that are flooded for much of the growing season with natural flood- or tide-waters or through irrigation. Upland rice, which accounts for just 10% of global rice production, is not flooded, and it is not a significant source of methane.

Methane is produced when organic matter in the flooded rice paddy is decomposed by bacteria and other micro-organisms. When soil is covered by water, it becomes **anaerobic**, or lacking in oxygen. Under these conditions, methane-producing bacteria and other organisms decompose organic matter in or on the soil, including rice straw, the cells of dead algae, other plants that grow in the paddy, and perhaps organic fertilizers such as manure. The outcome of this reaction is methane, carbon dioxide (but not in quantities significant for climate change), and other products:

Microbial metabolism : Plant Organic Matter + $H_2O \longrightarrow CH_4 + CO_2$ + other products

Methane is transported from the paddy soil to the atmosphere in three different ways. The primary method is through the rice plant itself, with the stem and leaves of the plant acting like pipelines from the soil to the air. This mode of transport probably accounts for 90-95% of emissions from a typical field. Methane also bubbles up directly from the soil through the water or is released into the air after first becoming dissolved in the water. Calculating how much methane is released from a particular field or region is difficult. Important variables include the number of acres under cultivation, the number of days that the paddy is submerged under water each year, and the rate of methane emission per acre per day. The uncertainty is caused by this last variable, which is complex and poorly understood. The methane emission rate is determined by soil temperature, the soil type, the type of rice grown, the amount and type of fertilizer applied, the average depth of water in the paddy, and other site-specific variables. Measurements at a fairly limited number of paddy sites have yielded a wide range of methane production rates. As a result, estimates of global methane production from rice paddies are considerably uncertain. One recent estimate gives a range of 20 - 150 million tons of methane per year (McCully 1991).

As rice is the staple food throughout much of Asia, nearly 90% of the world's paddy area is found there. China and India together have nearly half of the world's rice fields and probably contribute a similar fraction of the global methane emissions from rice production.

The options for reducing methane emissions from rice cultivation are limited. Reducing the area of rice under cultivation is unlikely to happen given the already tenuous food supply in many rice-dependent countries. Other options include replacing **paddy rice** with **upland rice**, developing strains of rice that need less time in flooded fields, and using different techniques for applying fertilizers. Each of these options will require much more research to become widely practical.

# 2

# Greenhouse Gases

## Instructor's Guide to Activities

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### Goal

In Unit 2 activities, students will learn to identify and distinguish between naturally produced and human produced greenhouse gases. They will also compare regional variations in greenhouse gas production and will understand their own personal contributions to greenhouse gas emissions by maintaining a personal energy log.

### Learning Outcomes

After completing the activities associated with this unit, students should be able to:

- construct a histogram or pie graph, by hand or with a computer
- distinguish between naturally produced and human produced greenhouse gases
- identify and quantify their personal contribution to greenhouse gas emissions
- analyze tabular data to assess regional variations in $CO_2$ and $CH_4$ emissions

### Choice of Activities

It is neither necessary nor feasible in most cases to complete all activities in each unit. Select activities that are most appropriate for your classroom setting and that cover a range of activity types, skills, genres of reading materials, writing assignments, and other activity outcomes. For this unit, the following activities are offered:

| | |
|---|---|
| 2.1 Regional Greenhouse Gas Emissions | -- data analysis, basic math, and comparison of results |
| 2.2 Personal Greenhouse Gas Emission Log | --log of daily activities and calculation of their contribution to GHG emissions |

### Suggested Readings

The following readings are suggested to accompany the activities for this unit. Choose those readings most appropriate for the activities you select and those most adequate for the skill level of your students.

- Unit 2: Greenhouse Gases (provided)
  The background information to Unit 2 (all students should read)

## Activity 2.1 Regional Greenhouse Emissions

### Goals

In this activity, students identify and distinguish between naturally produced and human produced greenhouse gases. Students will also make comparisons in regional greenhouse gas production.

### Skills

- ✓ constructing a histogram or pie graph, by hand or with a computer
- ✓ simple math (percentage calculations)
- ✓ concise, effective oral presentation
- ✓ teamwork, small group discussion

### Material Requirements

- Unit 2 Background Information (provided)
- Activity 2.1 Student Worksheet (provided)

### Time Requirements

1 class period (50 minutes)

### Tasks

This activity is intended as an in-class exercise. Students will answer questions on the Student Worksheet by referring to data in the provided tables. Using this same data, students will also construct histograms. Questions 2.1C and 2.1D are best answered in tandem by students working in pairs or groups. The instructor may choose to ask each pair or group to present their findings in a short (2 or 3 minute) presentation to the class.

## Activity 2.2 Personal Greenhouse Emissions Log

### Goals

Through a personal log of daily activities, students identify and quantify their personal contribution to greenhouse gas emissions.

### Skills

- ✓ identification of personal behavior and habits
- ✓ basic math
- ✓ concise, effective oral presentation

### Material Requirements

- Activity 2.2 Student Worksheet (provided)
- calculator

### Time Requirements

Students will complete most of this activity as homework. Allow ½ to 1 class period (25-50 minutes) for class discussion and for students to present and compare their results.

### Tasks

Activity 2.2 is a take-home assignment through which students gain insight into their personal activities that produce greenhouse gases. Students will keep a detailed log of their activities for a 24-hour period, especially those that involve using utilities and transportation, or that produce waste. Using this information, students will complete the Personal Energy Log in the Student Worksheet and calculate their contribution to greenhouse gas emissions. For those students living in communal dwellings (e.g., on campus), we suggest an alternative to this exercise by investigating the energy usage of the university or college, explored by students working in small groups. Students can focus on one aspect of the institution's energy usage (e.g., light bulbs, or heating and cooling) and investigate the usage level and efficiency of current materials, as well as alternatives that produce fewer greenhouse gases. You may need to facilitate this process by contacting the appropriate staff in the physical plant department and obtaining the records and other information students will need.

# 2 Greenhouse Gases

## Student Worksheets

Tables 2 and 3 below present the 1991 emissions of carbon dioxide and methane for major world regions by source. Analyze these tables and answer the questions below.

**Table 2: Regional Carbon Dioxide Emissions (% of Total $CO_2$ Emissions) in 1991**

| *Continent* | *Coal Burning* (%) | *Oil Burning* (%) | *Gas Burning & Flaring* (%) | *Cement Manufacture* (%) | *Land Use Change* (%) | *Total $CO_2$ Emissions* (1000 metric t) | *Per Capita $CO_2$ Emissions* (metric t) |
|---|---|---|---|---|---|---|---|
| S. Ameri. | 3.3 | 24.4 | 7.3 | 1.5 | 63.5 | 2,785,075 | 6.83 |
| N./ Centr. America | 35.4 | 41.2 | 22.2 | 0.7 | 0.4 | 5,454,262 | 19.39 |
| Asia | 43.7 | 33.5 | 7.0 | 3.7 | 12.1 | 7,591,529 | 2.43 |
| Africa | 20.9 | 19.5 | 9.0 | 1.9 | 48.8 | 1,311,794 | 2.04 |
| Europe | 41.2 | 38.9 | 16.8 | 3.0 | 0.0 | 4,113,759 | 8.08 |
| U.S.S.R. | 30.9 | 34.0 | 33.4 | 1.8 | 0.0 | 3,581,181 | 12.73 |
| Oceania | 48.6 | 28.1 | 12.9 | 1.2 | 9.1 | 3 17,769 | 11.90 |
| World | 32.9 | 36.4 | 15.4 | 2.3 | 13.0 | 26,076,496 | 4.92 |

Source: World Resources Institute. 1994. *World Resources 1994-95.* New York: Oxford University Press.

**Table 3: Regional Methane Emissions (% of Total $CH_4$ Emissions) in 1991**

| *Continent* | *Solid Waste* (%) | *Coal Mining* (%) | *Oil and Gas Production* (%) | *Wet Rice Agriculture* (%) | *Livestock* (%) | *Total $CH_4$ Emissions* (1000 metric t) | *Population 1990* (millions) |
|---|---|---|---|---|---|---|---|
| S. Ameri. | 10.6 | 1.6 | 6.3 | 4.8 | 74.0 | 21,700 | 407.6 |
| N./Centr. America | 29.7 | 30.1 | 18.9 | 2.3 | 20.9 | 32,300 | 276.6 |
| Asia | 6.8 | 14.2 | 2.7 | 55.8 | 20.8 | 120,000 | 3,117.8 |
| Africa | 8.8 | 10.0 | 6.3 | 16.3 | 60.0 | 16,000 | 642.6 |
| Europe | 51.7 | 11.7 | 9.0 | 0.8 | 26.6 | 29,000 | 509.0 |
| U.S.S.R. | 9.3 | 22.5 | 39.3 | 1.1 | 28.2 | 28,000 | 281.3 |
| Oceania | 11.3 | 26.8 | 7.1 | 1.2 | 53.6 | 5,600 | 26.7 |
| World | 15.7 | 15.7 | 10.2 | 28.5 | 30.1 | 252,600 | 5,295.3 |

Source: World Resources Institute. 1994. *World Resources 1994-95.* New York: Oxford University Press.

**A)** **Natural emissions of carbon dioxide and methane are approximately 706,000,000,000 and 250,000,000 metric tons per year, respectively. Calculate the human sources of $CO_2$ and $CH_4$ as a percent of natural sources for each GHG.**

Human $CO_2$ Percent = (World Human $CO_2$ / World Natural $CO_2$) x 100

= (                    /                    ) x 100 = __________ %.

Human $CH_4$ Percent = (World Human $CH_4$ / World Natural $CH_4$) x 100

= (                    /                    ) x 100 = __________ %.

**B) Your instructor will assign you (or your group) one of the seven regions/continents listed in Tables 2 and 3. Construct a histogram or pie graph of emissions by source for your continent for each of the two gases. The histograms or pie graphs can be constructed either by hand or by using an appropriate computer software package. Hand in your graphs on an extra sheet of paper.**

***How to construct a histogram***: The purpose of a histogram is to give an overview and comparison of frequencies or quantities. The typical format of a histogram is a bar chart. Draw two lines that intersect each other in a right angle on the left. Along the horizontal axis, mark five points equidistant from each other. At these points you will place the vertical bars, and the length of each bar will represent the percentage that a given human activity contributes to total carbon dioxide/methane emissions. Next, construct a scale along the vertical axis, e.g., 2 inches = 100% (thereby 1 inch = 50%, 0.5 inch = 25%, 0.1 inch = 5%, etc. Now calculate for each human activity how long the bar needs to be given the scale you have chosen. (Using the above scale, Africa's coal burning would be shown as a bar about 0.4 inch long).

***How to construct a pie chart***: A pie chart is another type of graph that depicts relative shares that something contributes to a larger total. Quite literally, if you had a round pie (=100%) and cut it into eight equally sized pieces, then each of your seven friends and you would get 1/8 of the pie or 10.25% of the total. In our activity, the "whole pie" is the total of a region's greenhouse gas emissions (for one kind of GHG at a time), and the differently seized pie pieces are the shares that each human activity contributes to this total. So, simply draw a circle and then a line from the center of the circle to its edge. Then overlay the circle (mentally or literally) with a "pie cutter" that divides the total into equal portions (e.g., into four quarters or into 10 10%-slices) -- this will simply help you to "eyeball" each activity's share in the circle. Line up your starting line with your "pie cutter" grid, and mark the relative portions of each human activity going around clockwise. If you want to, color the wedges. It may help you to read the pie chart.

**C) Answer the following questions for your region using your histogram/pie chart and the data presented in Tables 2 and 3. You may want to take notes on an extra sheet of paper. Be prepared to present your findings in a summary to the class.**

- How does your region rank in terms of per capita $CO_2$ emissions compared to other regions?
- How do your region's per capita $CO_2$ emissions compare to the world average per capita $CO_2$ emissions?

- What is the single largest source of $CO_2$ emissions for your region?
- What is the single smallest source of $CO_2$ emissions for your region?
- Which of the three fossil fuel sources (coal, oil, gas) is your region most dependent upon?
- How does your region's fuel mix compare to the world fuel mix[5]?
- How does your region rank in terms of total $CH_4$ emissions?
- What is the single largest source of $CH_4$ emissions for your region?
- What is the single smallest source of $CH_4$ emissions for your region?

**D)** Review the $CO_2$ and $CH_4$ emission profiles for each region and discuss the following questions with your group. Be prepared to present your findings to the class.

- Which region has the highest total emissions of carbon dioxide?
- Which region has the lowest total emissions of carbon dioxide?
- What factors explain the regional variations in $CO_2$ emissions?
- Which region has the highest total emissions of methane?
- Which region has the lowest total emissions of methane?
- What factors explain the regional variations in $CH_4$ emissions?

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[5] "Fuel mix" means the relative proportion of each fuel in the total of all fuels used, e.g., is the fuel mix dominated by one type of fuel, or is it a diverse mix?

# Student Worksheet 2.2

## Activity 2.2 Personal Greenhouse Gas Emissions Log

In this activity you will learn how your own actions produce greenhouse gases. The table below lists several activities you might regularly engage in. For one typical 24-hour day (e.g., midnight to midnight) keep a detailed log of what you do. In particular, list the activities that involve using utilities and transportation or that produce waste. Measure them in the appropriate units (how long did you use electricity? how much of it (kWh)? how much waste did you generate (kg, pounds)? ). There are more hints below on how to do that. When you have completed the worksheet, you will be able to compare your lifestyle with that of others in your class and see how much you contribute to the enhanced greenhouse effect.

**Helpful Hints in Completing Energy Log:**

a) ELECTRICITY USAGE: If you can't read your own meter, look at your last electric bill and then determine how many kilowatt-hours were used over a 24-hour period (if your statement is a monthly bill, divide the total kilowatt-hours used by the number of days in that month, or 30 for an average). One kilowatt-hour adds 1.5 pounds of $CO_2$ to the atmosphere. Record the number of kilowatt-hours used in the last 24 hours in the row headed "electricity," under the column with the heading "your use." (Note: if your generating facility is hydro, nuclear, or solar, your contribution will be 0. If you do not know how your electricity is generated, a quick call to your local power company will let you know.)

b) NATURAL GAS: If you use natural gas to heat your home, run the clothes dryer, heat your water, or generate your electricity, read your meter or look up your last gas bill. Again, determine how many cubic feet of natural gas you burned in a 24-hour period. For every 100 cubic feet of natural gas burned, you contribute 11 pounds of $CO_2$ to the atmosphere. Record your number in the row labeled "natural gas," under the "your use" column.

c) TRANSPORTATION: For every gallon of gasoline you use, you add 22 pounds of $CO_2$ to the atmosphere. Over the past 24 hours, how many gallons of gasoline did you use? Check your car's gas tank to find out, or else use a map to measure how many miles you drove and multiply this figure by how many miles per gallon your car can get. Do this for all means of transportation you used. In Table 4 of this worksheet, record these numbers in their respective rows.

d) GARBAGE: Collect everything you throw away in two bags, one for material you can recycle, one for other trash. At the end of the day, weigh both bags.

e) FILL IN ALL THAT APPLIES: Fill in all the rows that apply to you. Multiply the second column figures by the third column number provided and place the results in the last column.

f) DAILY SUB-TOTAL: Your *daily sub-total* will be the sum of the fourth column.

g) OTHER SOURCES: Many human activities and products add carbon dioxide to the atmosphere. Studies have indicated that all other sources roughly double the carbon dioxide you generated in the above three activities. So, double the daily subtotal that you calculated to arrive at your *daily total.*

h) PER CAPITA CALCULATION: If you live in a "family unit" divide your *Daily Total* by the number of people in your unit to estimate your personal (per capita) contribution. If you live alone, your total per capita per day will be the number you calculated for *Daily Total.* This number will be your *Per Capita Daily Total.*

i) ANNUALIZED CALCULATION: Since the above calculations above are for one day, estimate your annual contribution by multiplying your *Per Capita* number by 365. This will give you your *Annual Per Capita Total* GHG Production.

***After you completed the Energy Log, answer the following questions*** to prepare for class discussion (use an extra sheet of paper to take notes):

**A)** Which of your personal activities resulted in the greatest GHG production?

**B)** For comparison purposes, the average American family of four generates some 112,000 pounds per year. How do you, your family, your household, or school compare? What might be some reasons that your number is higher or lower than this average? Consider such factors as regional differences in climate, power generation, and affluence.

**C)** Bring your energy log to class and compare it with those of your classmates. What strikes you about your contributions to the greenhouse problem? How do your contributions differ from those of your classmates? Which portions of your lifestyle do you feel you have some control over, and which would you be willing to change? Commit to it!

Name ______________________________

## Table 4: Personal Energy Log
## Worksheet for Helping You Calculate Your Emissions

| Consumption or Activity | Your use (units per 24 hours) | $CO_2$ factor (lb $CO_2$/unit) | Daily emissions (lb $CO_2$ equiv.) |
|---|---|---|---|
| *Residential Utilities:* | | | |
| Electricity | kWh | 1.5 lb/kWh | |
| Oil | gallons | 22 lb/gal | |
| Natural gas | therms | 11 lb/therm | |
| | | | |
| *Transportation:* | | | |
| Automobiles | gallons | 22 lb/gal | |
| Other motor fuel use | gallons | 22 lb/gal | |
| Air travel | miles | 0.9 lb/mile | |
| Bus, urban | miles | 0.7 lb/mile | |
| Bus, intercity | miles | 0.2 lb/mile | |
| Railway or subway | miles | 0.6 lb/mile | |
| Taxi | miles | 1.5 lb/mile | |
| | | | |
| *Household Waste:* | | | |
| Trash (anything discarded) | pounds | 3 lb/lb | |
| Recycled items | pounds | 2 lb/lb | |
| *Daily Sub-total:* | | add all values in column 4 | |
| *Other Sources:* | | multiply daily sub-total by 2 | |
| *Daily Household Total:* | | add daily sub-total & other sources | |
| *Per Capita Daily Total:* | | divide by # persons in your household | |
| *Annual Per Capita Total:* | | multiply per capita daily total by 365 days | |

Source: Adapted from DeCicco, John *et al.* 1990. *$CO_2$ diet for a greenhouse planet: A citizen's guide to slowing global warming*, p.18. Audubon Policy Report # 1 "Bringing Science to Life." New York: National Audubon Society.

# 2 Greenhouse Gases

## Answers to Activities

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### Activity 2.1 Regional Greenhouse Gas Emissions

**A)** For the calculations in this question, students must recognize that the world natural $CO_2$ and world natural $CH_4$ figures presented in the text of the worksheet are in *metric tons*, whereas the figures for world human $CO_2$ and world human $CH_4$ figures presented in Table 2 and Table 3 are in *$10^3$ metric tons*. This means that the figures in the tables must be multiplied by 1,000 before the following calculations can be made.

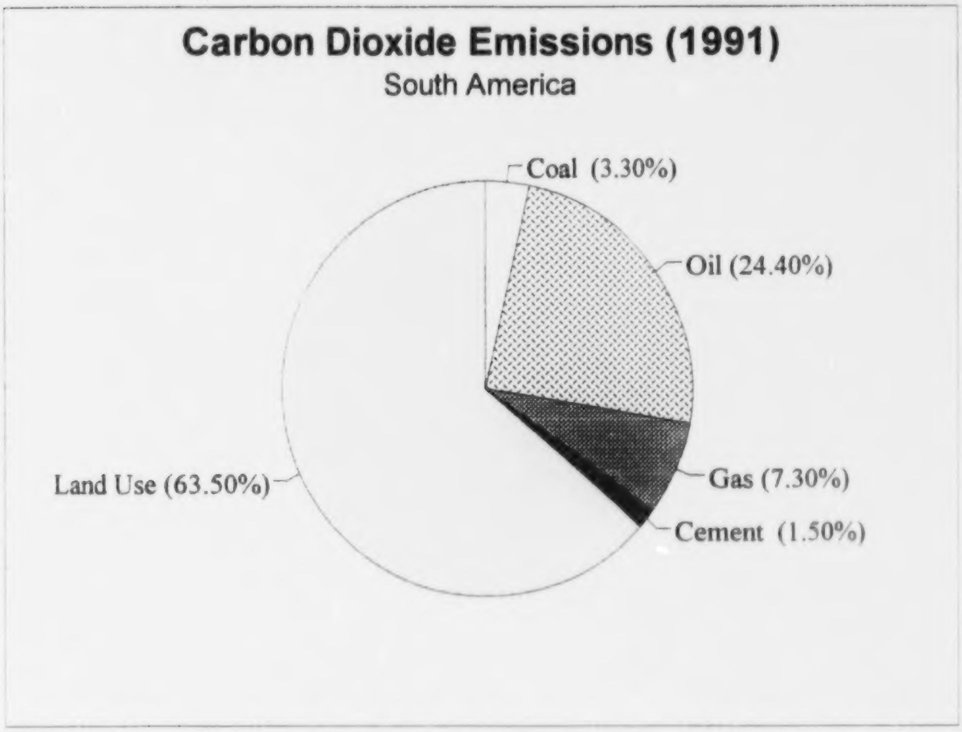
$$\text{Human } CO_2 \text{ Percent} = (\text{World Human } CO_2 / \text{World Natural } CO_2) \times 100$$

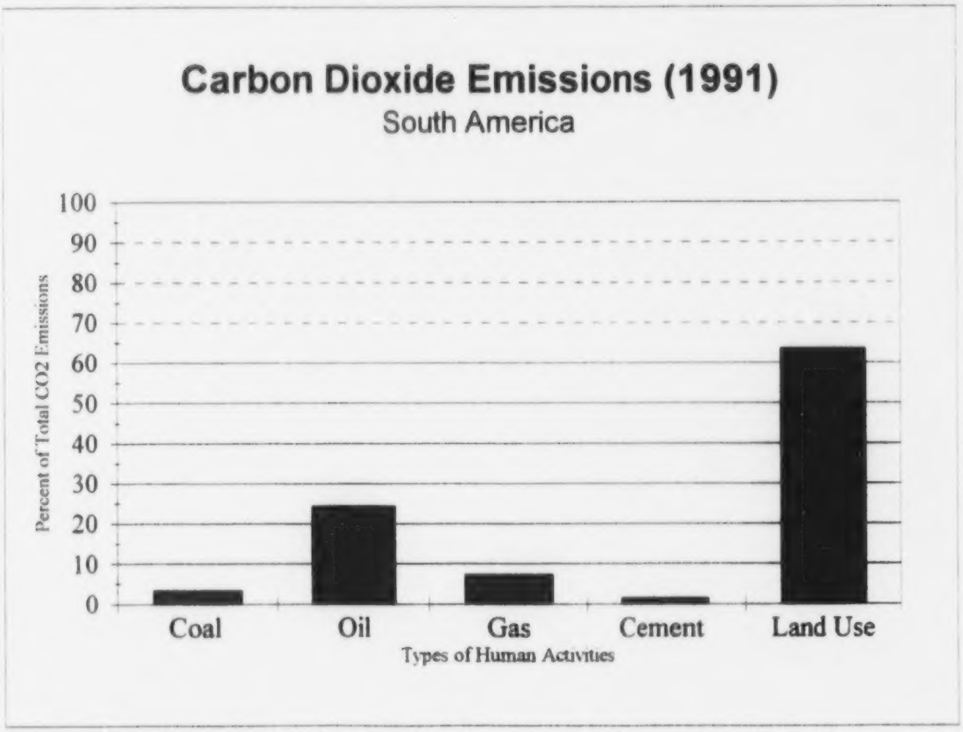
$$= (26/706) \times 100 = 3.7\,\%$$

$$\text{Human } CH_4 \text{ Percent} = (\text{World Human } CH_4 / \text{World Natural } CH_4) \times 100$$

$$= (\ 0.25/0.25\ ) \times 100 = 100\%$$

**B)** The illustrations on the following page are two examples of the kinds of histograms and pie charts students will construct.


Carbon Dioxide Emissions (1991)
South America


Carbon Dioxide Emissions (1991)
South America

**C)** The comparison of regions with regard to their $CO_2$ emissions the following observations can be made.

- Asia, North America, and Europe lead in total $CO_2$ emissions.
- Coal burning is of particular importance in Oceania, Asia, and Europe.
- Oil burning dominates the regional emissions in North America, Europe, and the (now former-) USSR
- A similar picture emerges for gas burning and flaring.
- Cement manufacture is generally a small contributor, but of some importance in Asia and Europe.
- Per capita emissions are highest in some of the highly developed regions of the world, especially North America. Per capita emissions in other developed regions may not be so high because averaging across the region brought the per capita figure down and/or because the region has achieved high energy efficiency.
- The fossil fuels used in a region depends on the natural resources available there and on trade relations. Coal dominates in Asia, Africa, and Oceania; oil leads in North America and the former USSR; gas is nowhere most significant, but is a close runner-up in the former USSR.
- Asia leads the total methane emissions by a large margin (owing to rice production).
- Methane emissions in South America are predominantly from livestock.
- A similar picture arises for Oceania; however, coal mining there makes up a significant share.
- In North America solid waste, coal mining, livestock, and oil and gas production are the leading causes of methane emissions.
- Africa is the only other region in which emissions from wetland rice production figures large, but livestock takes the prize in there.
- In Europe, interestingly enough, solid waste emits more than half of all methane.
- The picture in the former USSR resembles that of North America minus the waste.

**D)** The overall picture of carbon dioxide and methane emissions:

- The region with the highest carbon dioxide emissions is Asia.
- The region with the lowest carbon dioxide emissions is Oceania.
- The region with the highest methane emissions is Asia.
- The region with the lowest methane emissions is Oceania.
- One obvious reason for this pattern is population density in these regions. Another is the type of human activity that is prevalent there: agriculture with the goal of feeding billions of people; coal mining in China -- for Asia; and much smaller operations of both of these in Oceania.
- Livestock and wetland rice production account for a large part of the regional variation in methane emissions.

# 3 Estimating Regional and National Responsibility

## Background Information

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The issue of national and sectoral responsibility for global warming is highly controversial, pitting North vs. South, industry vs. individuals, coal vs. gas, and today's population vs. future generations. As the term *global* warming suggests, the entire world is both responsible and vulnerable. However, different parts of the world and different nations contribute more to the greenhouse effect than others. Different regions of the world are also differentially susceptible to the impacts of climate change, both because the degree of climate change may be more severe and because some nations are less able to adapt to or protect themselves from the consequences of climate change (Dow 1993). Responding to the problem obviously requires pinpointing the major anthropogenic sources of greenhouse gases and lowering those emissions. Determining the responsibility that each nation holds for producing gases that contribute to global warming, however, has proven to be a very thorny issue. Not only do many scientific unknowns surround what activities produce how much greenhouse gas, but many political issues arise in assessing the responsibility of nations with different historical industrial and land use patterns and with different numbers of people producing greenhouse gases. In this unit, we will examine these controversies and the scientific uncertainties involved.

## Greenhouse Gas Emission Indices

The debate about responsibility has centered around aggregate indices of greenhouse gas emissions. These indices estimate emissions of various greenhouse gases by using reports of fossil fuel use and other activities at the regional and national scale and then by combining the different gases into an index of carbon equivalents based on their radiative potential, the residence time, and other factors.

Existing indices include the rankings by the IPCC, the World Resources Institute (WRI), and the Centre for Science and Environment (CSE) in New Delhi, India. The weighting used in the IPCC ranking is the Global Warming Potential (GWP), while the WRI uses an index called the Greenhouse Forcing Contribution (GFC). CSE uses a much different approach emphasizing per capita emissions. It calculates natural sinks for carbon dioxide and methane on a global basis, allocates a share to each country according to its population, and then determines whether a country emits more than this sink allocation. As there are no natural sinks for CFCs, all CFC emissions are included.

## Scientific Uncertainties

Some of the scientific uncertainty in determining responsibility revolves around the task of determining exactly how much greenhouse gas is produced by what human activity. While -- as mentioned previously -- the data for $CO_2$ releases from fossil fuel burning are relatively reliable, estimates for $CO_2$ release caused by deforestation vary widely. Unknown factors include the exact amount of land deforested, the amount of carbon released by deforestation and soil disturbance, and the amount of carbon taken up by regrowth or turned into charcoal and therefore not released into the atmosphere (McCully 1991: 161). The release of methane from agricultural activities is another disputed issue. Rice paddies are a major source, but the contribution of methane from any one field depends on length of flooding, soil type, light, crop rotation, and fertilizer use. It is therefore quite difficult to generalize about methane emissions in paddies around the world. One estimate of emissions from wet rice cultivation in India, for example, states a methane release of 3-9 million tons while the World Resource Institute (WRI) estimates 18 million tons. A US-Chinese research team recently concluded that Chinese paddies contribute 30 million tons of methane a year (McCully 1991: 162). Methane emissions from livestock are also sensitive to the species and to the livestock feed mix, both of which are difficult to assess accurately.

There is also uncertainty about the radiative potential (ability to trap energy) and residence time in the atmosphere of $CO_2$ and methane and about whether CFCs have a net warming or cooling impact in their interaction with ozone.

The influence on atmospheric warming of different GHGs varies enormously. In 1990 $CO_2$ accounted for more than 98% by weight of the total emissions of the five main GHGs (low-level or tropospheric ozone is not considered here or elsewhere in this module because its impacts, although presumably large, are still difficult to quantify). Whatever time scale we consider, the contribution of $CO_2$ to the total effects of 1990 GHG emissions was much less than 98% because, ton-for-ton, it is the weakest of the main GHGs. As discussed earlier, the radiative effects of a particular greenhouse gas depend on the properties of the gas itself, as well as on the concentration in which it occurs in the atmosphere. The molecular properties of a greenhouse gas (GHG) determine how much infrared radiation it will absorb and in which wavelengths. This is clearly important, but we also need to know how much energy the gas is likely to encounter in those wavelengths as it drifts around in the atmosphere. Think of mud in a swimming pool: if you add a little mud to a clear swimming pool, the effect is immediately apparent. If you put the same amount of mud into a murky pool, you wouldn't notice any change because the pool was already opaque. Carbon dioxide, for example, occurs naturally, so the atmosphere is already partly opaque to wavelengths absorbed by $CO_2$. This reduces the direct impact of $CO_2$ emissions. So unlike CFCs, which did not exist in the atmosphere until humans introduced them, each additional kilogram of $CO_2$ has slightly less effect than the last one as the relevant wavelengths slowly "black out" (as the pool gets muddier, extra mud has less effect on its appearance).

Present GHG emissions will affect future GHG concentrations in different ways, depending on the particular "life cycle" of each gas. CFCs have the simplest life cycles. The only way the atmosphere gets rid of them is through their slow destruction by sunlight in the stratosphere. The average lifetime of CFC-11, for example, is 55 years. The other CFCs have lifetimes ranging from 90 to 400 years. Crucially, the lifetimes of the main CFC replacements (the hydro-chlorofluorocarbons, or HCFCs) are much shorter: typically about 15 years, which reduces their long-term effect on climate. Lifetimes of the other GHGs are somewhat harder to define, since their life cycles are too complex to be characterized by a simple decay process. Approximate lifetimes are 50-200 years for carbon dioxide, 10 years for methane, and 130 years for nitrous oxide.

Additional uncertainties become apparent when we try to compare the relative importance of the different greenhouse gases. We will look at the individual indices that are used to compare greenhouse gases in more detail below; for now, let's just use the IPCC's index to demonstrate some of these uncertainties. That index tries to get at the relative importance of different GHG emissions through their Global Warming Potentials (GWPs). For methane, for example, the direct GWP is defined as the cumulative direct effect on the atmosphere's energy budget resulting from a one-kilogram release of methane, relative to the direct effect of a one-kilogram release of $CO_2$. In calculating this cumulative effect, it is necessary to specify the time horizon over which we are interested in the impact of a particular gas. As discussed above, the reason for this is that different greenhouse gases have different cycles and residence times in the atmosphere. Of every molecule of a greenhouse gas that we emit today, most will still be there in 10 years, but only some will be left in 50 years, and even fewer will remain for as long as 100 years.

The choice of time horizon strongly influences the relative importance we assign to current emissions of each greenhouse gas. The Intergovernmental Panel on Climate Change (IPCC) calculates GWPs for three reference time horizons: 20, 100, and 500 years. The 20-year horizon is relevant for short-term impacts, such as changes in weather patterns; the 100-year horizon applies to longer time scale changes, such as sea-level rise; and the 500-year horizon represents the longest time scale that is reasonable given our current knowledge. On short time scales, 1990s $CO_2$ emissions contribute more than half the direct effects of 1990s total GHG emissions, and methane almost 30%. Because methane has such a short lifetime, the relative importance of 1990 methane emissions is much lower for longer time horizons.

At present, scientists can only calculate GWPs for the *direct* climatic effects of a gas, but the *indirect* effects resulting from complex feedbacks may also be very important. GHGs interact with each other and with other gases in the atmosphere. For example, the chemical reactions that destroy methane also produce water vapor, which can have a significant warming effect, particularly when the vapor occurs at high altitudes. This may increase the total climatic impact of methane emissions by 5-40%. On the other hand, CFCs destroy ozone in the stratosphere. By doing so, they may largely compensate for their own direct impact as GHGs. These various indirect effects are still not understood well enough to be quantified in terms of GWPs, leaving large uncertainties unresolved.

Estimates of GWPs based on current knowledge must be regarded as indicative at best. They must therefore be used with great caution in formulating policy. The impact of policies that involve trade-offs between one GHG and another (such as replacing coal with natural gas, which would reduce $CO_2$ but might increase methane emissions) is especially uncertain, because current models of both gases' life cycles (and thus their relative GWPs) may need to be revised in the future. Despite these caveats, the IPCC and the World Resources Institute (WRI) have developed indices to indicate the relative contributions to GHGs.

## The IPCC's Global Warming Potential

The IPCC Global Warming Potential (GWP) takes into account the radiative potential the time horizon over which the different gases are emitted to and remain within the atmosphere and the chemical breakdown of one gas into another. The time horizons used by IPCC were 20, 100, and 500 years into the future, and the GWP of each molecule of greenhouse gas (GHG) was estimated in relation to the reference index of 1 for $CO_2$.. The GWP of each GHG was estimated for the world as a whole rather than individual countries. For instance, for the 20-year time horizon, methane has a GWP of 35 and nitrous oxide 260, meaning that these gases are more powerful than $CO_2$ in causing global warming by a factor of 35 and 260, respectively. These GWP's can be multiplied by the total emissions of each gas estimated from scenarios of future energy use to compare different policy options and regional trends.

The GWP has become a focus of scientific discussion and research regarding the uncertainties in atmospheric chemistry and the role of different gases in warming the Earth's atmosphere. The GWP is politically important because it compares gases emitted in very different proportions over different periods of time by different countries. According to IPCC estimates, 95% of the fossil fuel $CO_2$ emissions are from the more industrially developed Northern Hemisphere. Furthermore, deforestation in the temperate zones produced the greatest releases of $CO_2$ in the 19th and early 20th centuries -- about 0.5 billion tons a year.

## The WRI's Greenhouse Gas Index

A major controversy has risen around the efforts of the World Resources Institute (WRI) to establish a "greenhouse gas index," a single number that clarifies each country's responsibility for global warming. The controversy has provided a focus for much of the recent debate about responsibility and provides a useful example of the science and difficulties involved.

WRI's index aims to rank each country according to its total contribution to greenhouse gases. The original index combined emissions of carbon dioxide, methane, and CFCs, taking into account their different radiative potentials. The index only accounted for responsibility for the current year's increase in greenhouse gases by estimating the proportion of the annual release of each greenhouse gas that remains in the atmosphere at the end of a year. This proportion was multiplied by the relative efficiency of that gas in absorbing longwave radiation (the radiative potential) and by the total national emissions of that gas to arrive at an emission estimate in tons of carbon. The totals for the three gases are added to come up with the overall index, which was also expressed in tons per capita by dividing by the population (World Resources Institute 1990: 14, 353; McCully 1991: 158).

For example, Costa Rica's annual emission of $CO_2$ from fossil fuels and cement was estimated for 1987 at 320,000 tons of carbon, with an added 6,600,000 tons from land use change (primarily deforestation). Methane emissions from solid waste, livestock, and rice totaled 17,000 tons, which converted to 330,000 tons of carbon because methane has a higher radiative potential than $CO_2$. CFC emissions were 300 tons, converting with CFCs very high radiative potential to 490,000 tons of carbon. The combined index was 7,800,000 tons of carbon added to the atmosphere in one year by Costa Rica -- or 2.6 tons per capita (World Resources Institute 1990-91: Table 24.2).

WRI's reports receive wide media recognition and are viewed by many as the most trustworthy and up-to-date sources of information. Critics, on the other hand, have worried about the widespread acceptance of these reports and think that they are biased against developing nations. These critics point out that not only do the reports ignore uncertainties over data about the greenhouse gas emissions from deforestation and agriculture; they also fail to take historical and per capita emissions into account, or to consider the difference between "luxury" and "survival" emissions (Agarwal and Narain 1991; McCully 1991; see also Unit 4).

By lumping different factors into a single number, the critics say, the WRI index obscures many scientific uncertainties in the calculations, and furthermore produces results that account only for current emissions. This approach ignores the large amount of atmospheric greenhouse gases produced over the last century and a half by industrialized nations, thereby discriminating against nations that have a shorter history of industrialization (Thery 1992: 88-89).

Critics also point out that on a per capita basis, the developing nations emit far less than their share of current greenhouse gases. The IPCC estimates average per capita carbon emissions from most developing countries to be 0.6 tons per capita per year compared to 5 tons per year for industrialized countries (IPCC 1990: 10).

The 1990 IPCC report estimated that carbon emissions from global deforestation in 1980 ranged anywhere from 0.6 to 2.6 billion tons (IPCC 1990: 5). The 1990 WRI report, for instance, uses the high end of this range in its ranking of Brazil's average annual carbon contributions in the 1980s (McCully 1991: 162). WRI estimates that global deforestation, most of it in tropical regions like Brazil and Indonesia, was responsible for 2.8 billion tons of carbon in 1987 and 3.4 billion tons in 1991, or some 15% of total 1991 human $CO_2$ emissions (WRI 1994: 361, 364).

WRI not only estimates high amounts of carbon from deforestation but also cites deforestation rates that are higher than those cited in other reports and ignores the decline in the rate of deforestation in Brazil during the last several years. The WRI report estimates an average annual deforestation rate in Brazil of 3.7 million hectares from 1981 to 1990 (WRI 1994: 305). Only in footnotes does the report mention Brazil's disputed and declining deforestation rate. Other reports, for example, state that the rate is down from about 2 million hectares a year between 1978 and 1988 to 1.1 million hectares in 1990-91 (WRI 1994: 313).

# 3 Estimating Regional and National Responsibility

## Instructor's Guide to Activities

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### Goal

In the activities associated with this unit, students identify the nations and regions with the highest/lowest $CO_2$ emissions and explain regional variations in GHG emissions. Students will also consider differing international perspectives on GHG emission controls and examine the relationships among GHG production, population, and per capita GNP.

### Learning Outcomes

After completing the activities associated with this unit, students should be able to:

- construct and interpret a choropleth map
- identify geographic patterns and temporal trends in greenhouse gas emissions
- read and interpret greenhouse gas emissions data in graphs and tables
- have a basic understanding of differing perspectives on global greenhouse gas emissions policy

### Choice of Activities

It is neither necessary, nor feasible in most cases to complete all activities in each unit. Select activities that are most appropriate for your classroom setting and that cover a range of activity types, skills, genres of reading materials, writing assignments, and other activity outcomes. For this unit, the following activities are offered:

| | |
|---|---|
| 3.1 Regional Greenhouse Gas Emissions | --creating choropleth maps of activities contributing to $CO_2$ emissions |
| 3.2 National Profiles of GHG Production | --analysis of country-level emissions data and short answers |
| 3.3 Patterns and Trends in Human Activities Producing Greenhouse Gases | --analysis of graphs for spatial and temporal variations in greenhouse gas emissions |

### Suggested Readings

- Unit 3: Estimating Regional and National Responsibility (provided)
  The background information to Unit 3 (all students should read)

## Activity 3.1 Regional Greenhouse Gas Emissions

### Goals

The purpose of this activity is for students to identify and explain regional variations in greenhouse gas emissions. Students will create choropleth maps to illustrate the spatial patterns of activities that contribute to $CO_2$ emissions.

### Skills

- ✓ constructing a choropleth map
- ✓ data classification
- ✓ logical and critical thinking

### Material Requirements

- ✓ Activity 3.1 Student Worksheet (provided)
- ✓ $CO_2$ Emissions from Industry and Land Use Change by Country for 1991 (provided)
- ✓ base maps (provided in *Supporting Materials*; copy as needed)[6]
- ✓ color pencils
- ✓ calculator

### Time Requirements

1 to 2 class periods (50-100 minutes)

### Tasks

Activity 3.1 is an in-class assignment that asks students to estimate regional and national responsibility for GHG production. Students will use the data provided to create choropleth maps. Using this information, students answer the questions posed on the student worksheet. The best way to approach this activity is to divide the class into small groups and allocate approximately ten countries to each group. Have students work together as they go through the procedures for classifying the data in the first column of the data table. Then have each group split in half with one-half working through the procedures for column 2 and the other half working on column 3. The group should then reconvene and answer the questions.

## Activity 3.2 National Profiles of Greenhouse Gas Emissions

### Goals

In this activity, students focus on nine countries throughout the world with varying levels of greenhouse gas emissions. Students will examine data on the activities that produce these emissions within the countries in order to gain insight into each country's perspective on greenhouse gas emissions policies.

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[6] Providing base maps of the world inevitably leads to the problem of mismatch between a rapidly changing world and a constant, soon-to-be-outdated map. For the politically most correct and up-to-date map, instructors are advised to find latest versions in their map library, on the World Wide Web, or from the most recent version of AtlasGIS or a similar mapping software.

### Skills

- ✓ data analysis and interpretation
- ✓ logical and critical thinking

### Material Requirements

- Activity 3.2 Student Worksheet

### Time Requirements

½ class period (25 minutes); may also be assigned as a homework exercise.

### Tasks

Using the data presented in the student worksheets, students answer several short questions that are intended to highlight the relationships between a country's greenhouse gas producing activities and its perspective on greenhouse gas emissions policies. This is a short exercise that may be combined with Activity 3.3 and completed as a homework exercise.

## Activity 3.3 Patterns and Trends in Human Activities Producing Greenhouse Gases

### Goals

The purpose of this activity is for students to identify and examine geographic patterns and temporal trends in greenhouse gas emissions.

### Skills

- ✓ interpreting scatterplots
- ✓ logical and critical thinking

### Material Requirements

- Activity 3.3 Student Worksheet
- Scatterplots (Figures 6, 7, and 8a-i; provided)

### Time Requirements

½ class period (25 minutes); may also be assigned as a homework exercise

### Tasks

Students use the data provided to answer the questions on the student worksheet. The questions are intended to make students identify relationships between greenhouse gas emissions and GNP and population. Students will also identify geographic patterns and temporal trends in greenhouse gas emissions. This is a short activity that may be combined with Activity 3.2.

# 3 Estimating Regional and National Responsibility

## Student Worksheets

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### Activity 3.1: Regional Greenhouse Gas Emissions

#### Introduction

In this exercise you will learn fundamental choropleth map construction skills, using either a computer program like AtlasGIS or drawing the maps by hand. A choropleth map is a map in which the color or shading of areas varies according to the density, concentration, or magnitude of a phenomenon. For example, if you drew a population map on which you wanted to show how population density varied across space, you would show all those areas with similar population densities in the same shade or color. So, generally speaking, a choropleth map shows data across space by showing groups of like data in similar shades or colors for a given area. In this activity you will create choropleth maps illustrating spatial patterns of activities that contribute to $CO_2$ emissions.

#### Instructions

Table 5 presents total emissions of carbon dioxide for each nation in the world for 1991. The three columns of data are: column 1) total industrial $CO_2$ emissions (in 1000s of metric tons) (sum of coal burning, oil burning, gas burning, cement manufacturing, and gas flaring); column 2) per capita industrial $CO_2$ emissions (in metric tons); and column 3) total $CO_2$ emissions from land use changes (in 1000s of metric tons).

Use the data in the table to map (and examine) national emissions of carbon dioxide. The maps may be created either by hand or using a computer mapping software package. Your instructor will tell you which nations you (or your group) are to map.

To create your choropleth maps you must select the appropriate data, group the data for each nation into classes, assign the classes a pattern or color, create a map, and annotate it. Let's outline this procedure step by step.

1. *Selection of data*
   Once you have been assigned a region to map, locate all of the respective nations within your region in the table. You may want to circle or highlight these values in the table.

2. *Group the data into classes*

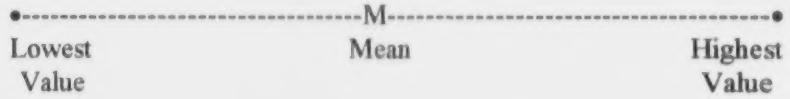
Now you have the data needed to create your choropleth maps. A map that used a different shade or color for each of these numbers would be confusing. You can simplify the data (and thereby the overview that the map is supposed to provide) by creating groups or classes into which your nations fall. Thus, you'll be using a small number of ranges (or classes), which will make the map much easier to comprehend visually.

**REMEMBER: You will need to do each of the following steps three times (one for each column of data in the table)**

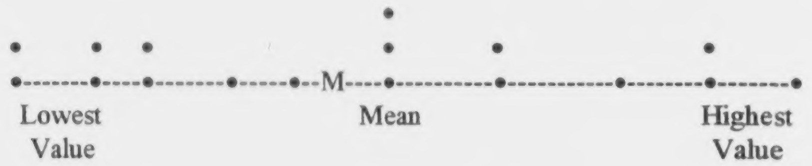
a) Determine the **range** of the values (identify the lowest and highest values) and mark this range (the two extreme values) on the axis below:

Lowest Value
Highest Value

b) Obtain the mean by adding both values and dividing the sum by 2, then plot the **mean** value for the region on the graph:



c) Plot all other values as **data points** (•) on the graph:



d) Divide these data points into classes. As you do, keep the following in mind:

- Create a **small number of classes**. (You may want to try creating four class intervals and use a fifth class interval for "no data.")

- Each class must be **discrete**. This means that an observation can fall only into one class, e.g., form classes from 0-5, 6-10, 11-15, etc.

- Choose the intervals of numbers (class size) that define each class. You can make intervals/class size **constant** (which will most likely result in having uneven numbers of objects (nations) in each class), or you can make the intervals **variable** (while having an equal number of objects in each class). You could do this by choosing to divide the observations between natural breaks in the data. Try both ways and see what effects each approach would have on your resulting map.

Note: If in (c) above you have a very skewed distribution, meaning most points are on one side of the mean, it will not make much sense to have an equal class size because most points would fall in one or two classes and none in the remaining classes. Plus, the variability among nations in the area where they are concentrated would be entirely lost. Your intervals should simplify things and at the same time convey as much information as possible.

3. *Assign the classes a color*

This is the art (and fun) of cartography: choose a color pattern that will best illustrate the data in a way that a reader can quickly understand and interpret the phenomenon you are mapping. Here are some simple rules of good color patterns:

- The **highest** class should be the darkest color;
- The **lowest** class should be the lightest color;
- Use the colors **within the same family or hue range**. Cartographic tests demonstrate that choropleth maps with colors in a similar range are easiest for map readers to understand. For example, use a color range of reddish brown, to red, to orange, and to yellow;
- Reserve **blank** or white for "no data."

4. *Create the maps*

Use the base maps for your region provided by your instructor. (Remember, you will need three copies of your regional base map -- one for each data column in the table). Make extra copies of your blank base maps in case you have problems! Each country will fall into one of the classes you have defined and should be **carefully illustrated** with the pattern or color you have chosen.

5) *Add a title, legend, and the source to your map*

a) The **Title** summarizes what the map is about. Include the name of the region and the year of the data.
For example: "*Map of Gross National Product for Europe, 1987*"

b) The **Legend** illustrates the assigned color pattern for each class of data and gives the unit of measurement of the data.

c) The **Source** tells the reader where you found the data and the date of that publication.
For example: "*World Resources Institute, 1991*"

If you want to see some examples of choropleth maps, their color schemes, titles, legends, and source annotations, look through any atlas.

When your maps are finished, answer the questions on the student worksheet. If you worked in groups, discuss the maps with each other. All of you should take notes on your discussion and be able to present your answers to the rest of the class.

## Table 5: $CO_2$ Emissions from Industry and Land Use Change by Country (1991)

| ID | Name | Total industrial $CO_2$ emissions (1000s of metric tons), (sum of coal burning, oil burning, gas burning, cement manufacture, & gas flaring) | Per capita industrial $CO_2$ emissions (metric tons) | Total $CO_2$ emissions from land use change (1000s metric tons) |
|---|---|---|---|---|
| AF | Afghanistan | 5147.92 | 0.29 | |
| AL | Albania | 6247.12 | 1.91 | |
| DZ | Algeria | 55194.50 | 2.16 | |
| AO | Angola | 4788.85 | 0.51 | 16000 |
| AG | Antigua | 289.46 | 4.36 | |
| AR | Argentina | 115848.40 | 3.55 | |
| AU | Australia | 261818.40 | 15.10 | |
| AT | Austria | 60331.42 | 7.80 | |
| BS | Bahamas | 1945.58 | 7.47 | |
| BH | Bahrain | 10050.35 | 19.38 | |
| BD | Bangladesh | 15443.76 | 0.15 | 6800 |
| BB | Barbados | 1011.26 | 3.92 | |
| BE | Belgium | 102079 | 10.22 | |
| BT | Bhutan | 128.24 | 0.07 | 4100 |
| BO | Bolivia | 5855.07 | 0.81 | 140000 |
| BW | Botswana | 2154.43 | 1.69 | 3200 |
| BR | Brazil | 215600.80 | 1.43 | 970000 |
| BZ | Belize | 263.81 | 1.36 | 840 |
| SB | Solomon Islands | 161.22 | 0.48 | |
| BN | Brunei | 5605.92 | 21.21 | |
| BG | Bulgaria | 56674.75 | 6.30 | |
| BI | Burundi | 219.84 | 0.04 | 120 |
| KH | Cambodia | 461.66 | 0.04 | 34000 |
| CM | Cameroon | 1923.60 | 0.15 | 23000 |
| CA | Canada | 410628.10 | 15.21 | |
| CV | Cape Verde | 84.27 | 0.22 | |
| CF | Cen. Afr. Rep. | 208.85 | 0.07 | 23000 |
| LK | Sri Lanka | 4165.97 | 0.26 | 3700 |
| TD | Chad | 252.82 | 0.04 | 7100 |
| CL | Chile | 32525.33 | 2.42 | |
| CN | China | 2543380.00 | 2.20 | |
| CO | Colombia | 57502.82 | 1.76 | 100000 |
| KM | Comoros | 65.95 | 0.11 | |
| CG | Congo | 2015.20 | 0.88 | 12000 |
| ZR | Zaire | 4235.58 | 0.11 | 280000 |
| CR | Costa Rica | 3249.97 | 1.06 | 12000 |
| CU | Cuba | 34397.63 | 3.22 | 2800 |
| CY | Cyprus | 4481.07 | 6.34 | |
| EZ | Czech Republic | 191356.10 | 12.20 | |
| BJ | Benin | 560.59 | 0.11 | 3000 |
| DK | Denmark | 63053.78 | 12.24 | |
| DM | Dominica | 58.62 | 0.81 | |

| ID | Name | Total industrial $CO_2$ emissions (1000s of metric tons), (sum of coal burning, oil burning, gas burning, cement manufacture, & gas flaring) | Per capita industrial $CO_2$ emissions (metric tons) | Total $CO_2$ emissions from land use change (1000s metric tons) |
|---|---|---|---|---|
| DO | Dominican Rep. | 6261.78 | 0.84 | 4800 |
| EC | Ecuador | 17785.06 | 1.65 | 68000 |
| SV | El Salvador | 2531.82 | 0.48 | 290 |
| GQ | Equat. Guinea | 120.91 | 0.33 | 2600 |
| ET | Ethiopia | 2824.94 | 0.07 | 8000 |
| EE | Estonia | 575.25 | 12.20 | |
| FJ | Fiji | 688.83 | 0.95 | |
| FI | Finland | 52047.12 | 10.41 | |
| FR | France | 374112.70 | 6.56 | |
| GF | French Guiana | 696.16 | 6.89 | |
| DJ | Djibouti | 359.07 | 0.81 | |
| GA | Gabon | 5986.98 | 5.02 | 47000 |
| GM | Gambia | 197.86 | 0.22 | 94 |
| DE | Germany | 969630.00 | 12.13 | |
| GH | Ghana | 3455.15 | 0.22 | 15000 |
| KI | Kiribati | 21.98 | 0.29 | |
| GR | Greece | 72865.97 | 7.18 | |
| GL | Greenland | 542.27 | 9.71 | |
| GD | Grenada | 120.91 | 1.32 | |
| GT | Guatemala | 4074.37 | 0.44 | 20000 |
| GN | Guinea | 1025.92 | 0.18 | 9800 |
| GY | Guyana | 850.05 | 1.06 | 6500 |
| HT | Haiti | 732.80 | 0.11 | -57 |
| HN | Honduras | 1945.58 | 0.37 | 17000 |
| HK | Hong Kong | 29132.46 | 5.06 | |
| HU | Hungary | 63574.06 | 6.05 | |
| IS | Iceland | 1802.69 | 7.00 | |
| IN | India | 703550.30 | 0.81 | 21000 |
| ID | Indonesia | 170467.60 | 0.92 | 330000 |
| IR | Iran | 222360.80 | 3.70 | |
| IQ | Iraq | 42355.84 | 2.27 | |
| IE | Ireland | 32235.87 | 9.23 | |
| IL | Israel | 35566.45 | 7.29 | |
| IT | Italy | 402516.00 | 6.96 | |
| CI | Ivory Coast | 6379.02 | 0.51 | 9900 |
| JM | Jamaica | 4671.60 | 1.91 | 7000 |
| JP | Japan | 1091147.00 | 8.79 | |
| JO | Jordan | 10010.05 | 2.42 | |
| KE | Kenya | 4847.47 | 0.18 | 360 |
| KP | North Korea | 243234.60 | 10.96 | |
| KR | South Korea | 264647.10 | 6.05 | |
| KW | Kuwait | 11842.05 | 5.68 | |
| LA | Laos | 252.82 | 0.07 | 36000 |
| LB | Lebanon | 8361.25 | 3.00 | |
| LS | Lesotho | | | |

| ID | Name | Total industrial $CO_2$ emissions (1000s of metric tons), (sum of coal burning, oil burning, gas burning, cement manufacture, & gas flaring) | Per capita industrial $CO_2$ emissions (metric tons) | Total $CO_2$ emissions from land use change (1000s metric tons) |
|---|---|---|---|---|
| LR | Liberia | 274.80 | 0.11 | 7400 |
| LY | Libya | 43008.03 | 9.12 | |
| LU | Luxembourg | 10310.50 | 27.48 | |
| MO | Macao | 1088.21 | 2.27 | |
| MG | Madagascar | 1073.55 | 0.07 | 20000 |
| MW | Malawi | 630.21 | 0.07 | 10000 |
| MY | Malaysia | 61196.13 | 3.33 | 110000 |
| MV | Maldives | 95.26 | 0.44 | |
| ML | Mali | 436.02 | 0.04 | 8400 |
| MT | Malta | 1663.46 | 4.65 | |
| MQ | Martinique | 1363.01 | 3.74 | |
| MR | Mauritania | 2704.03 | 1.28 | -1 |
| MU | Mauritius | 1216.45 | 1.14 | |
| MX | Mexico | 339872.60 | 3.92 | 50000 |
| MN | Mongolia | 9823.18 | 4.36 | |
| MD | Moldavia | 29.31 | 2.78 | |
| MA | Morocco | 24197.06 | 0.95 | |
| MZ | Mozambique | 1029.58 | 0.07 | 14000 |
| OM | Oman | 11695.49 | 7.40 | |
| NA | Namibia | | | |
| NR | Nauru | 131.90 | 13.19 | |
| NP | Nepal | 923.33 | 0.04 | 7600 |
| NL | Netherlands | 138990.20 | 9.23 | |
| VU | Vanuatu | 65.95 | 0.44 | |
| NZ | New Zealand | 23841.65 | 6.96 | |
| NI | Nicaragua | 2073.82 | 0.55 | 32000 |
| NE | Niger | 1029.58 | 0.15 | |
| NG | Nigeria | 91929.76 | 0.81 | 10000 |
| NO | Norway | 58671.63 | 13.74 | |
| PK | Pakistan | 68487.49 | 0.55 | 9700 |
| PA | Panama | 3594.38 | 1.47 | 21000 |
| PG | Papua New Guinea | 2257.02 | 0.59 | 29000 |
| PY | Paraguay | 1780.70 | 0.40 | 28000 |
| PE | Peru | 19155.39 | 0.88 | 94000 |
| PH | Philippines | 44587.22 | 0.70 | 110000 |
| PL | Poland | 308164.40 | 8.06 | |
| PT | Portugal | 41791.58 | 4.25 | |
| GW | Guinea-Bissau | 205.18 | 0.22 | 1700 |
| PR | Puerto Rico | 12006.93 | 3.37 | |
| QA | Qatar | 19646.37 | 44.66 | |
| RE | Reunion | 1106.53 | 1.80 | |
| RO | Romania | 138026.50 | 5.94 | |
| RW | Rwanda | 436.02 | 0.07 | 71 |
| KN | St. Kitts | 73.28 | 1.76 | |
| LC | Saint Lucia | 161.22 | 1.21 | |

| ID | Name | Total industrial $CO_2$ emissions (1000s of metric tons), (sum of coal burning, oil burning, gas burning, cement manufacture, & gas flaring) | Per capita industrial $CO_2$ emissions (metric tons) | Total $CO_2$ emissions from land use change (1000s metric tons) |
|---|---|---|---|---|
| ST | Sao Tome | 69.62 | 0.59 | |
| SA | Saudi Arabia | 214919.20 | 13.96 | |
| SN | Senegal | 2799.30 | 0.37 | 4600 |
| SC | Seychelles | 131.90 | 1.87 | |
| SL | Sierra Leone | 688.83 | 0.15 | 1800 |
| SG | Singapore | 41293.28 | 15.06 | |
| VN | Vietnam | 20573.36 | 0.29 | 33000 |
| SO | Somalia | 523.95 | 0.07 | 360 |
| ZA | South Africa | 278694.80 | 7.18 | |
| ZW | Zimbabwe | 16982.64 | 1.65 | 4100 |
| ES | Spain | 219876.60 | 5.64 | |
| SD | Sudan | 3403.86 | 0.15 | 38000 |
| SR | Surinam | 2018.86 | 4.69 | 4800 |
| SZ | Swaziland | 329.76 | 0.44 | |
| SE | Sweden | 53498.06 | 6.23 | |
| CH | Switzerland | 41842.88 | 6.16 | |
| SY | Syria | 29766.34 | 2.31 | |
| TH | Thailand | 100895.60 | 1.83 | 91000 |
| TG | Togo | 721.81 | 0.18 | 2100 |
| TO | Tonga | 73.28 | 0.77 | |
| TT | Trinidad | 18429.92 | 14.73 | 1100 |
| TU | Tunisia | 14809.89 | 1.80 | |
| TR | Turkey | 142555.20 | 2.49 | |
| TM | Turkmenistan | 912.34 | 0.00 | |
| UG | Uganda | | 0.04 | 4700 |
| RU | U.S.S.R | 3581179.00 | 12.31 | |
| EG | Egypt | 81666.90 | 1.54 | |
| GB | Britain | 577156.90 | 10.00 | |
| TZ | Tanzania | 2158.10 | 0.07 | 21000 |
| US | United States | 4931630.00 | 19.53 | 22000 |
| BF | Burkina Faso | 556.93 | 0.07 | 3400 |
| UY | Uruguay | 4459.09 | 1.43 | |
| VE | Venezuela | 121604.50 | 6.16 | 170000 |
| WS | Western Samoa | 124.58 | 0.81 | |
| YM | Yemen | 9940.43 | 0.81 | |
| YU | Yugoslavia | 87225.18 | 3.66 | |
| ZM | Zambia | 2429.23 | 0.29 | 33000 |

Source: World Resources Institute. 1994. *World Resources 1994-95*, excerpted from their Tables 23.1 and 23.2, pp. 362-365.

Name________________________

## Activity 3.1 Questions

A) Which countries have the highest **total** industrial emissions of carbon dioxide? Why?

B) Which countries have the highest **per capita** industrial emissions of carbon dioxide? Why?

C) Are there any countries that rank high on both total and per capita industrial emissions? If so, which countries are they, and how would you explain this?

D) Which countries have the highest total land use change emissions of carbon dioxide? Why?

E) What generalizations can you make in the relationship among total industrial emissions, per capita industrial emissions, and land use emissions?

## Student Worksheet 3.2 Name:

### Activity 3.2 National Profiles of Greenhouse Gas Production

### Introduction

This activity focuses on nine countries from throughout the world with varying levels of carbon dioxide, methane, and CFC emissions. By examining the human activities that produce the GHGs in each country, we shall gain insight into each country's perspective on global GHG emissions policy. Your instructor will assign a country to you (or your group) for this activity.

### Instructions

Using data from Tables 6 and 7, analyze the economic and land use activities that contribute to $CO_2$, $CH_4$, and CFC emissions for your country. If you find it hard to read the tables, transform them as you did earlier into histograms or pie charts to assist your analysis and explanation. Then answer the questions below. Use an extra sheet of paper if you need more space. If you work in a group, discuss the questions with each other, each of you taking notes, and one of you presenting your group's answer to the rest of the class.

*Questions:*

A) Which activities produce the highest emissions of **carbon dioxide** in your country, and how do you think this relates to resource use and the economy?

B) Which activities produce the highest emissions of **methane** in your country, and how do you think this relates to resource use and the economy?

C) What perspectives do you think your country would bring to an International Environmental Conference on GHG emissions? Will your country seek to limit emission reductions or demand reductions from all countries?

### Table 6: Carbon Dioxide Emissions (1000s metric tons) of Selected Countries in 1991/92

| *Country* | *Coal Burning* | *Oil Burning* | *Gas Burning* | *Gas Flaring* | *Cement Manufacture* | *Land Use Changes* | *Per Capita GNP (US$)* |
|---|---|---|---|---|---|---|---|
| Brazil | 39,875 | 153,492 | 8,028 | 1,674 | 14,004 | 1,100,000 | 2,930 |
| China | 2,088,011 | 398,291 | 30,239 | 0 | 151,4371 | 150,000 | 364* |
| Germany | 404,681 | 324,781 | 129,229 | 758 | 18,686 | -20,000† | 23,560 |
| Ghana | 7 | 3,265 | 0 | 0 | 509 | 18,000 | 430 |
| India | 551,897 | 161,333 | 22,420 | 8,874 | 24,915 | 65,000 | 300 |
| Japan | 317,790 | 622,294 | 108,191 | 0 | 45,195 | 0* | 31,490 |
| S. Arabia | 0 | 124,385 | 66,047 | 22,504 | 7,683 | 60 | 7,953 |
| U.S.S.R.* | 1,105,766 | 1,216,320 | 1,172,733 | 23,074 | 63,288 | n/a | 2,350 |
| U.S.A. | 1,786,167 | 1,986,042 | 1,065,227 | 8,973 | 34,944 | 22000* | 24,740 |

Sources: World Resources Institute. 1994. *World Resources 1994-95*. New York: Oxford University Press; WRI. 1996. *World Resources 1996-97*. New York: Oxford University Press; Tables 14.1, 14.2, 7.2, and 14.6.

* Values are for 1991

† Negative values indicate a $CO_2$ sink, i.e., the land use change took up more carbon dioxide than it emitted.

### Table 7: Methane and CFC Emissions (1000s metric tons) of Selected Countries in 1991/92

| *Country* | *Solid Waste* | *Coal Mining* | *Oil & Gas Production* | *Wet Rice Agricult.* | *Livestock* | *CFCs** | *Population (in 1000s)‡* |
|---|---|---|---|---|---|---|---|
| Brazil | 1,300 | 3 | 190 | 350 | 8,100 | 4 | 161,790 |
| China | 890 | 15,000 | 260 | 24,000 | 7,000 | 8 | 1,221,462 |
| Germany | 1,400 | 700 | 220 | 0. | 1,100 | 23 | 81,591 |
| Ghana | 29 | 0 | 0 | 23 | 76 | 1 | 17,453 |
| India | 2,600 | 2,200 | 830 | 16,000 | 11,000 | 3 | 935,744 |
| Japan | 1,900 | 84 | 36 | 310 | 1,600 | 64 | 125,095 |
| S. Arabia | 330 | 0 | 2,200 | 0 | 83 | 2 | 171,880 |
| U.S.S.R.* | 2,600 | 6,300 | 11,000 | 320 | 7,900 | 44 | 281,300 |
| U.S.A. | 8400 | 9100 | 5300 | 750 | 6000 | 90 | 263,250 |

Source: World Resources Institute. 1994. *World Resources 1994-95*. New York: Oxford University Press; WRI. 1996. *World Resources 1996-97*. New York: Oxford University Press, Tables 14.2, 8.1.

* Values for 1991 ‡ Population in 1995

# Student Worksheet 3.3 Name:

## Activity 3.3 Patterns and Trends in Human Activities Producing Greenhouse Gases

This activity examines the geographic patterns and trends over time of greenhouse gas emissions. The countries selected for Activity 3.2 are also used in this activity.

Examine Figures 6 and 7 on the following page.

A) Describe the relationship between total industrial $CO_2$ emissions per capita and GNP per capita.

B) Describe the relationship between total industrial $CO_2$ emissions and total population.

C) How might these relationships affect international efforts to control GHG emissions?

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Figures 8a-i on the next few pages illustrate trends in per capita industrial $CO_2$ emissions for several countries from 1970 to 1991. What is not shown here, but generally holds true, is that the time trends of carbon dioxide emissions are related to economic development and population growth.

D) Discuss the trends for the country you have focused on so far, and try to explain short-term variations in emissions.

E) Now examine Figure 8j which plots all nine countries on a single graph. What do you observe when all nine plots are shown on a single plot?

Figure 6: Total Industrial $CO_2$ Emissions per capita vs. GNP per capita for Selected Countries in 1991

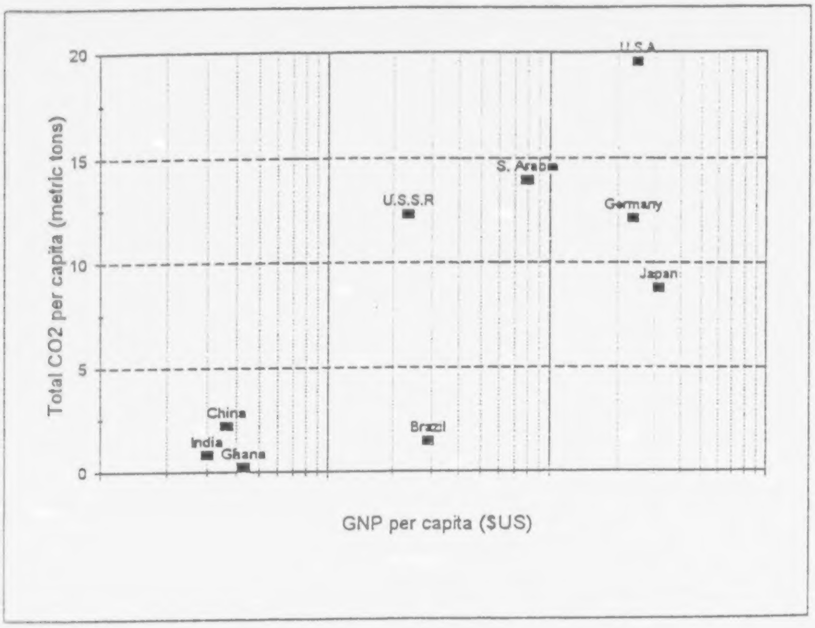

Figure 7: Total Industrial $CO_2$ Emissions vs. Population for Selected Countries in 1991

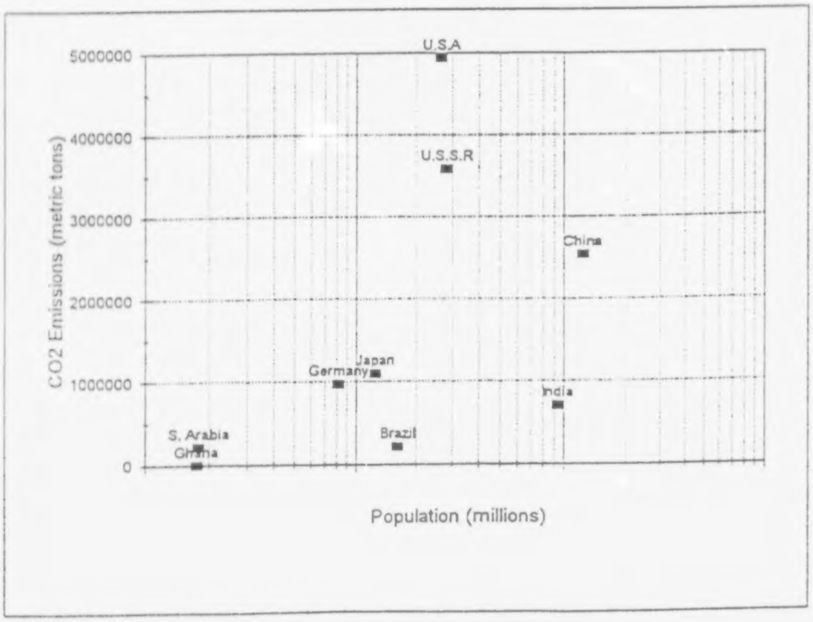

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Figure 8a

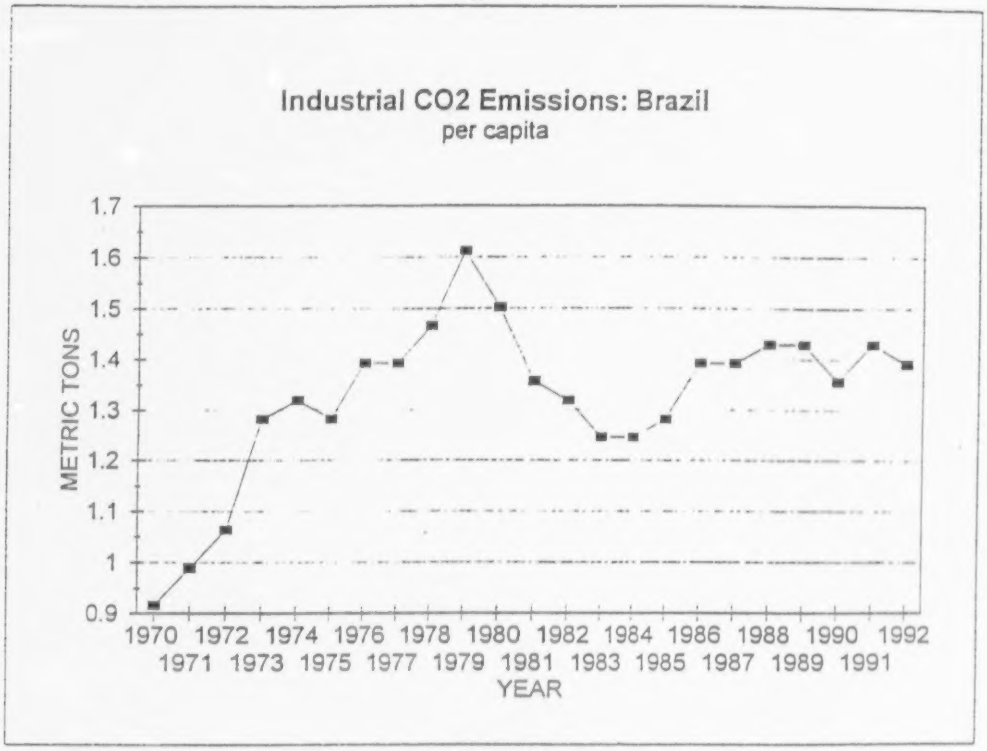
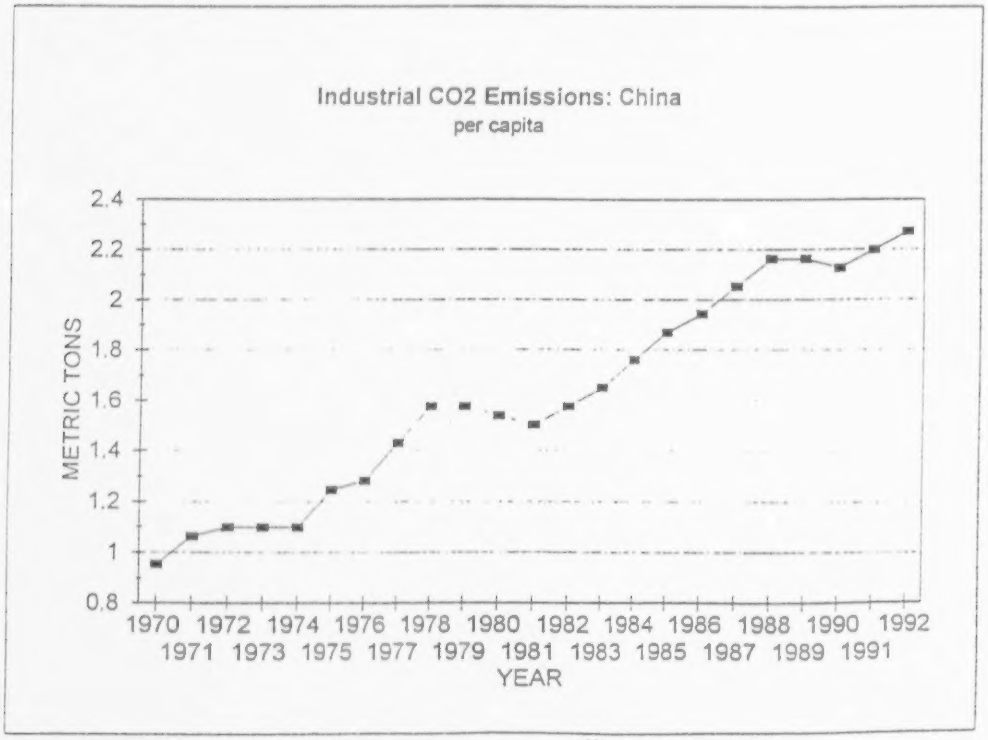
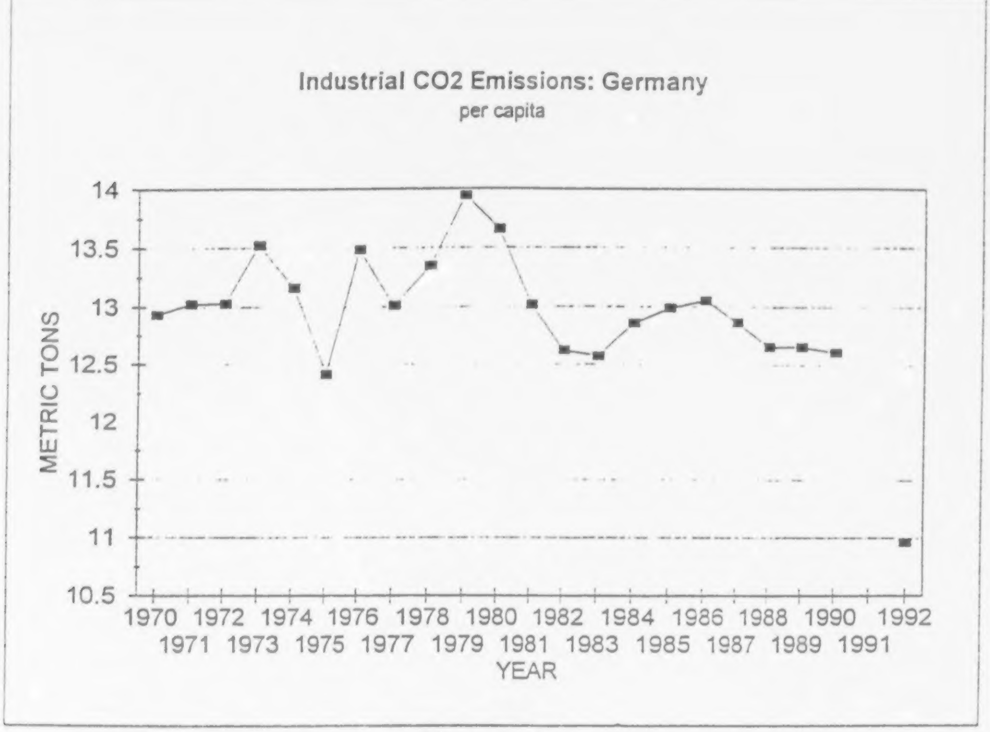


Figure 8b



## Figure 8c



## Figure 8d

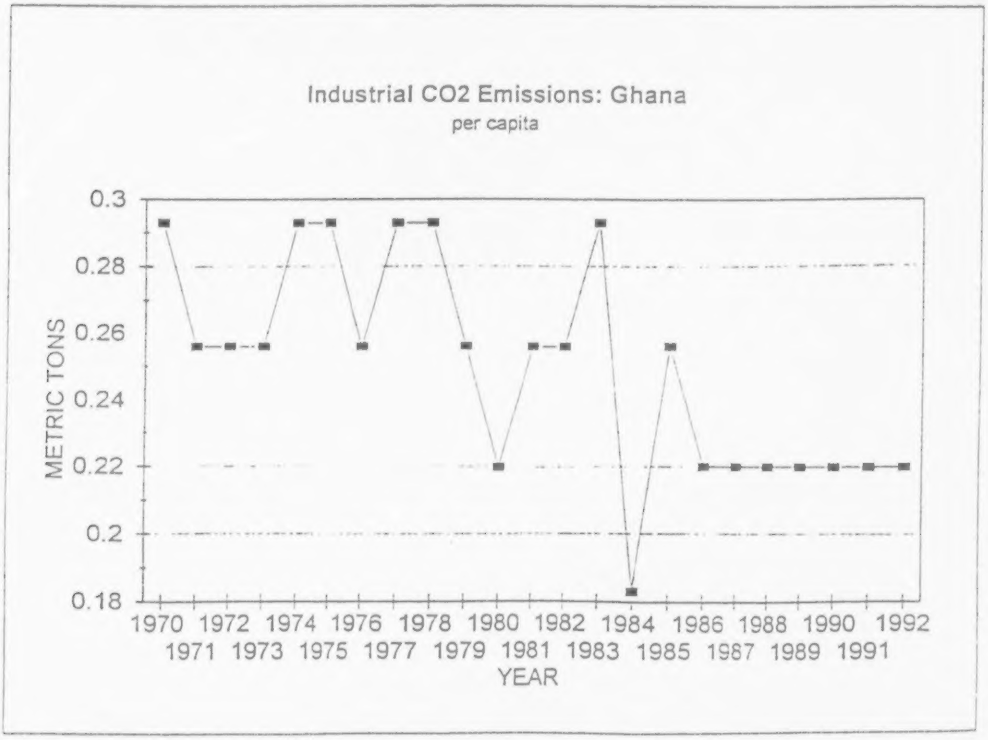


Figure 8e

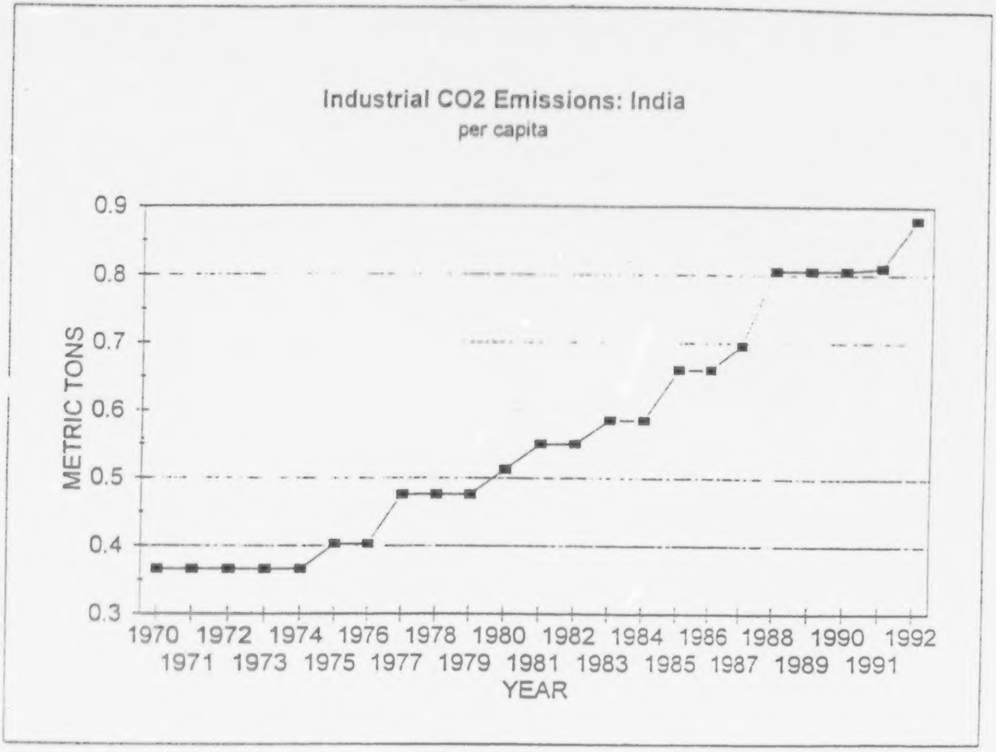


Figure 8f

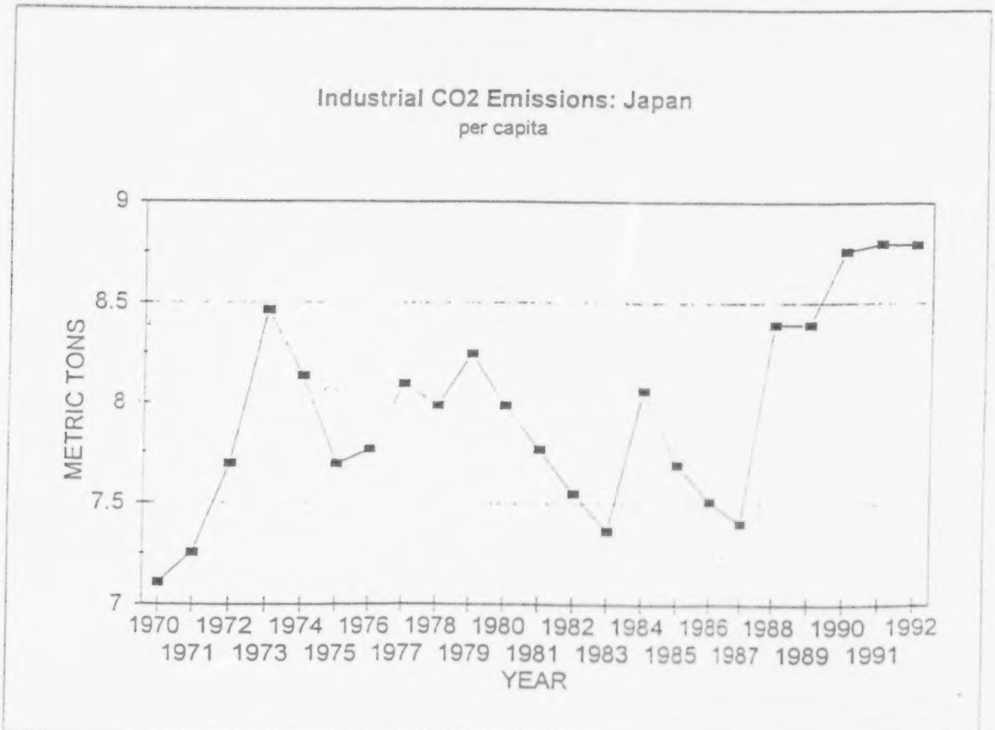


Figure 8g

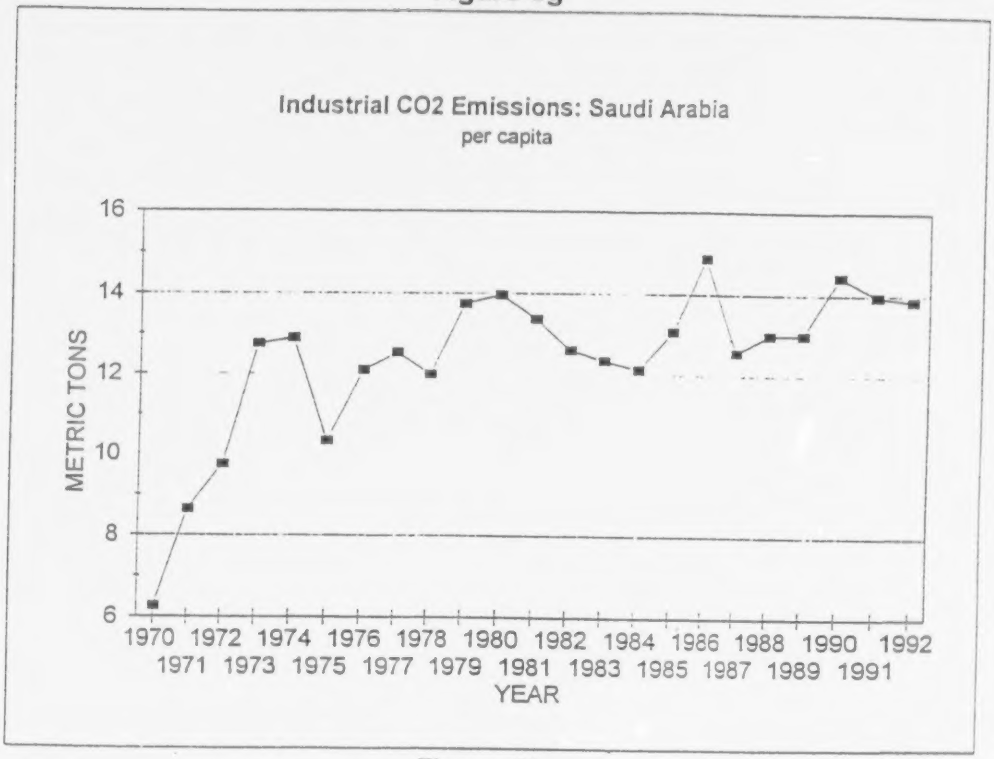


Figure 8h

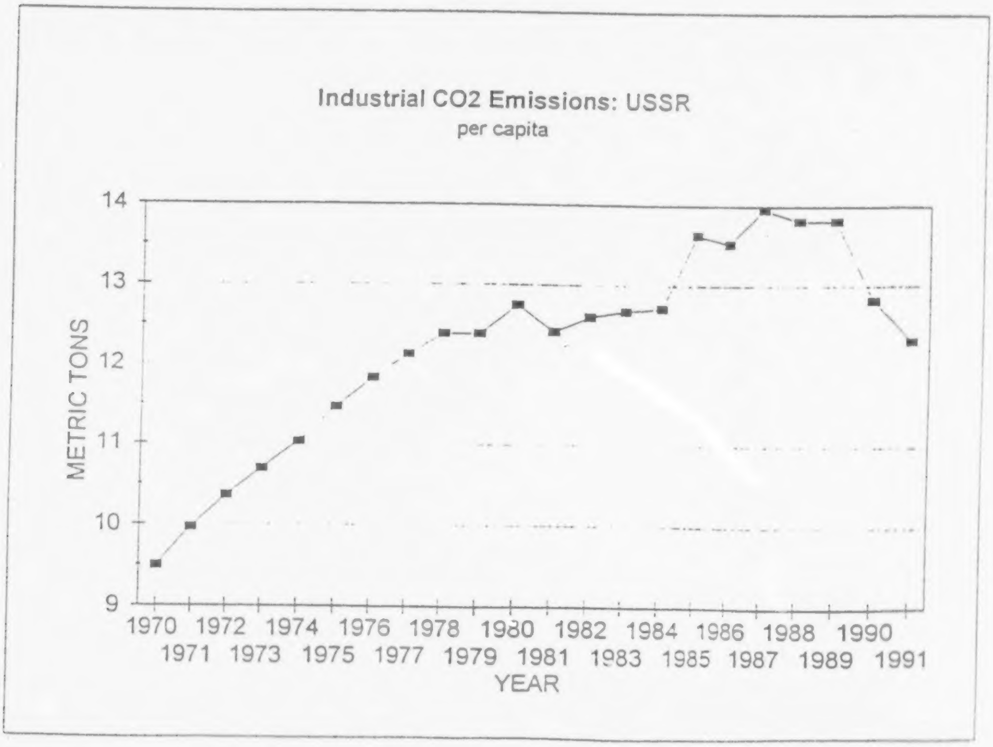


**Figure 8i**

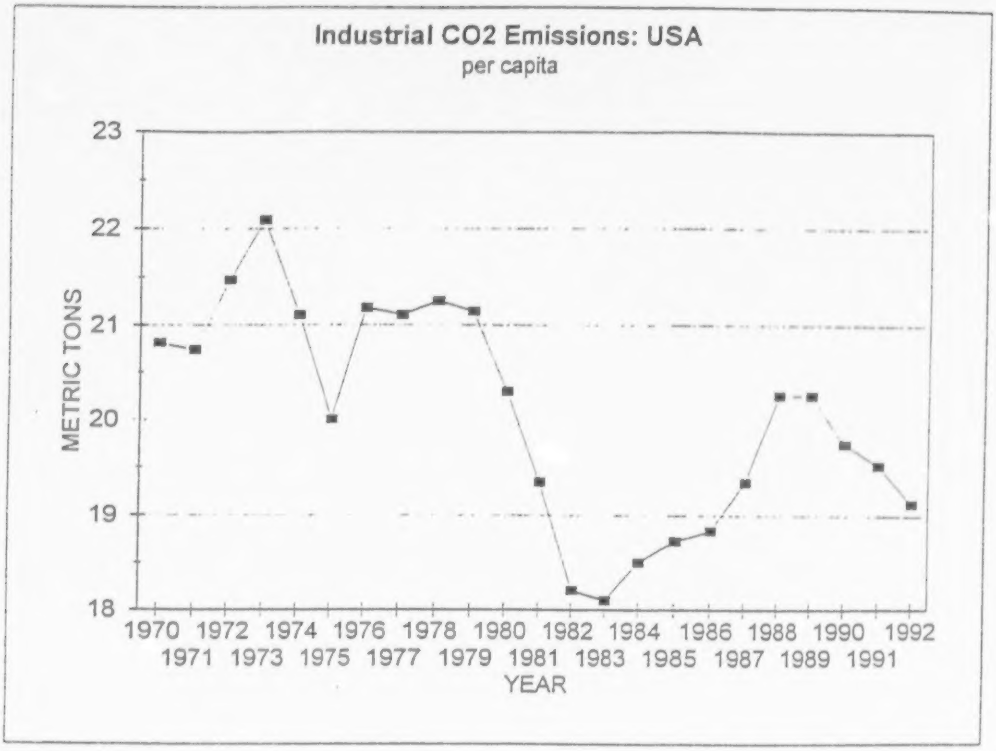
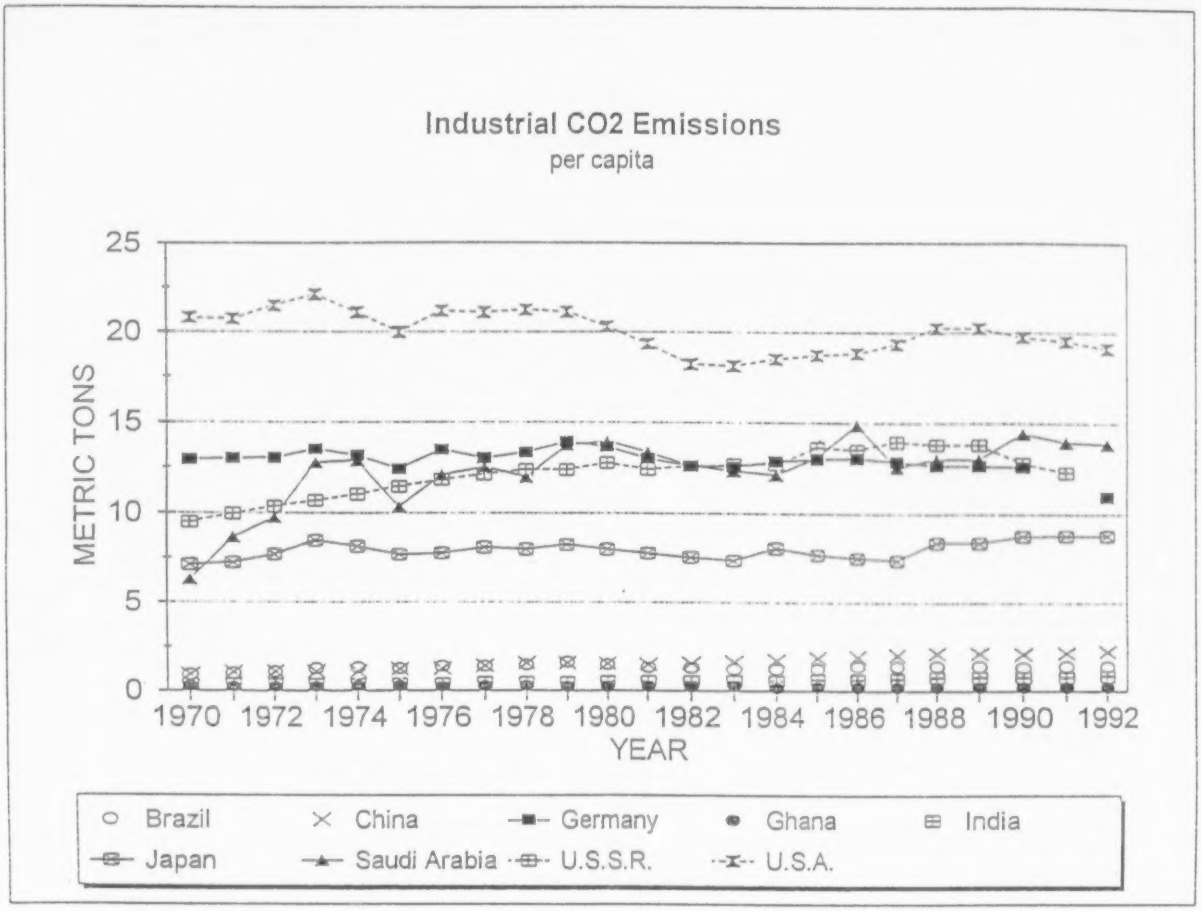

Industrial CO2 Emissions: USA
per capita
23
22
21
20
19
18
METRIC TONS
1970 1972 1974 1976 1978 1980 1982 1984 1986 1988 1990 1992
1971 1973 1975 1977 1979 1981 1983 1985 1987 1989 1991
YEAR

**Figure 8j**


Industrial CO2 Emissions
per capita
METRIC TONS
25
20
15
10
5
0
1970
1972
1974
1976
1978
1980
1982
1984
1986
1988
1990
1992
YEAR
Brazil
China
Germany
Ghana
India
Japan
Saudi Arabia
U.S.S.R.
U.S.A.

# 3 Estimating Regional and National Responsibility

## Answers to Activities

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### Activity 3.1: Regional Greenhouse Gas Emissions

Below, choropleth mapping is shown for only one region and one column of data. The example is subjective in that our choice of class intervals and shading may differ from those produced by students. The steps from data to map are illustrated first. You may use this example before students do other regions to demonstrate how it should be done.

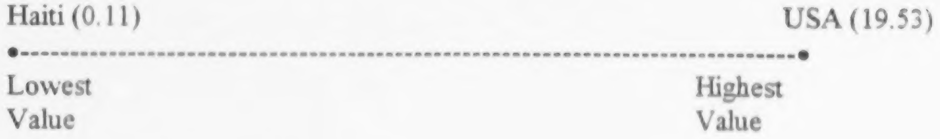
1) *Selection of data:*

Region -- North and Central America
Column -- Per capita industrial $CO_2$ emissions
Data (in metric tons) for the following countries:

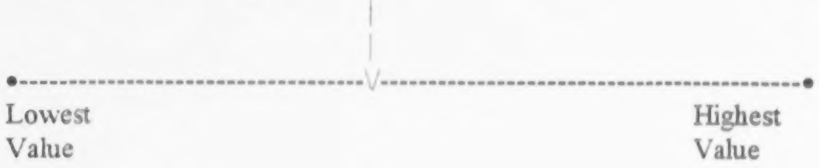
| | |
|---|---|
| Canada | 15.21 |
| USA | 19.53 |
| Mexico | 3.92 |
| Cuba | 3.22 |
| Dominican Republic | 0.84 |
| Dominica | 0.81 |
| Bahamas | 7.47 |
| Haiti | 0.11 |
| Jamaica | 1.91 |
| Puerto Rico | 3.37 |
| Antigua | 4.36 |
| Barbados | 3.92 |
| St. Lucia | 1.21 |
| Grenada | 1.32 |
| Belize | 1.36 |
| Guatemala | 0.44 |
| Honduras | 0.37 |
| El Salvador | 0.48 |
| Nicaragua | 0.55 |
| Costa Rica | n/a |
| Panama | 1.47 |
| Colombia | 1.76 |
| Venezuela | 6.16 |
| Guyana | 1.06 |

2) *Group the data into classes*:

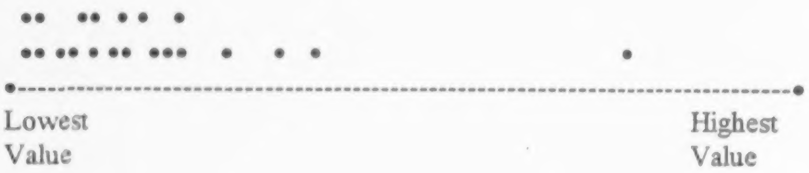
a)


Haiti (0.11)
USA (19.53)
Lowest Value
Highest Value

b) The mean value for the region: 9.82


Lowest Value
Highest Value

c) Plot all other values on the graph:



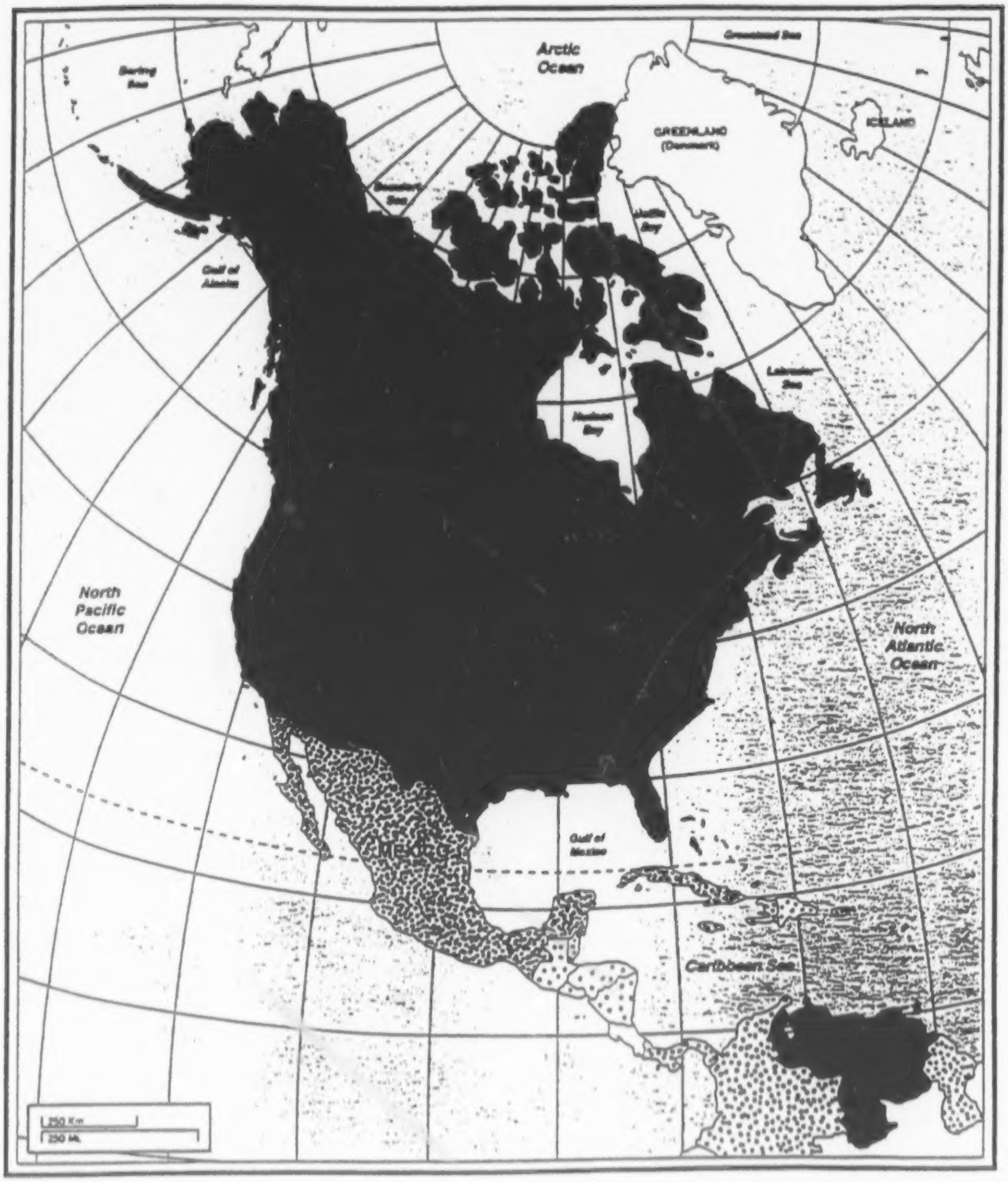
(Note: The data points at the lower end of this scale are too close together to be shown in their exact positions.)

d) Divide these data points into classes.

| | | |
|---|---|---|
| Class 1: | 0- 0.99 | ░ |
| Class 2: | 1- 2.99 | ▒ |
| Class 3: | 3- 4.99 | ▓ |
| Class 4: | 5-19.99 | ■ |
| Class 5: | no data | ☐ |

3) *Map the data*: see the regional map of North and Central America on the following page. (Shading, title, source, and legend as shown there.)

## Per capita $CO_2$ Emissions for North and Central America in 1991
(in metric tons)


Arctic Ocean
Greenland Sea
Bering Sea
GREENLAND (Denmark)
ICELAND
Beaufort Sea
Baffin Bay
Gulf of Alaska
Labrador Sea
Hudson Bay
North Pacific Ocean
North Atlantic Ocean
Gulf of Mexico
Mexico
Caribbean Sea
250 Km
250 Mi.

Legend:

0- 0.99 ⁘

1- 2.99 ▨

3- 4.99 ▩

5-19.99 ■

no data ☐

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Answers to questions on Activity 3.1 Student Worksheet:

The answers to these questions will vary depending on the regions or countries that students are assigned to investigate. The following responses are based on the North and Central American (and parts of South American) regions used above.

A) Which countries have the highest **total** industrial emissions of carbon dioxide? Why?

The U.S. has the highest total industrial emissions of carbon dioxide. Canada is the next highest. The U.S. is a highly industrialized country, and oil and coal burning are very important energy sources.

B) Which countries have the highest total **per capita** industrial emissions of carbon dioxide? Why?

The U.S. has the highest total per capita industrial emissions of carbon dioxide. The U.S. has high total emissions and a relatively small population, so consequently the per capita emissions are high.

C) Are there any countries that rank high on both total and per capita industrial emissions? If so, which countries are they and how would you explain this?

In this case, the U.S. ranks high on both total and per capita industrial emissions. The explanations for questions A and B above support this. (More interesting results may be possible for this question based on the region investigated.)

D) Which countries have the highest total land use change emissions of carbon dioxide? Why?

Venezuela and Colombia have the highest total land use change emissions of carbon dioxide from the countries depicted on the map. These countries have experienced high rates of deforestation. Note: These countries would not be the highest if they were examined within the entire South American continent. Brazil has a much higher total land use change emissions of carbon dioxide. These countries appear high here relative to the more industrialized parts of North America where deforestation occurred decades earlier. They are included here simply because they are within the scope of the map used in the examples above.

E) What generalizations can you make regarding the relationship among total industrial emissions, per capita emissions, and land use emissions?

In this case, those countries with the highest total industrial emissions (U.S., Canada), also have the highest per capita emissions and negligible land use change emissions. Countries with high land use change emissions appear to have relatively low total and per capita emissions.

## Activity 3.2: National Profiles of Greenhouse Gas Production

The answers below indicate some of the points students should make in their answers. Summaries are given for each country under each question.

A) Which activities produce the highest emissions of carbon dioxide in your country and how do you think this relates to resource use and the economy?

Brazil: Land use change; followed by oil burning; -- deforestation foremost and other land use changes cause this predominance.

China: Coal burning, followed by oil burning; -- China's current development toward industrialization is largely based on and driven by coal exploitation and the ensuing heavy industry. China also has the largest population of any nation for which electricity is being supplied.

Germany: Coal and oil burning make up the largest activities from which $CO_2$ is emitted. -- Germany has coal and oil reserves and its fairly strong heavy industry depends on it. Energy efficiency is comparatively high.

Ghana: Land use changes are by far the most important activities in this West African country. Again, land use for agricultural production is at the forefront. Oil burning indicates beginning industrialization and intensifying economic development.

India: Coal burning is the lead emitting activity. See explanations for China and Ghana.

Japan: Oil, and secondarily coal-burning are Japan's lead emitters, closely tied to this country's high industrialization standard (with relatively high energy efficiency).

S. Arabia: Saudi Arabia's oil burning is at the top of the list. The country has no coal but immense oil reserves; and its industry is entirely based on this energy resource. Efficiency is not perceived as necessary or even desirable, since the country's main source of income is from oil sales.

USSR: The former USSR is rich in fossil fuel resources, quite inefficiently produced and used. The country had a large population, large area, and industry that heavily depended on these energy resources.

USA: The world's single largest carbon dioxide emitter has oil and coal burning as its "dirtiest" activities. A wasteful, high-consuming, and quite inefficient economy must be sought as reasons.

B) Which activities produce the highest emissions of methane in your country and how do you think this relates to resource use and the economy?

Brazil: Livestock. Cattle raising on land that used to be covered by tropical forests. Thus, carbon dioxide emissions and methane emissions are closely tide in this country.

China: Wet rice agriculture, followed by coal mining. -- The huge coal mining operations were mentioned previously. Rice is the main staple in the Chinese/Asian diet (see population figures).

Germany: Solid waste and livestock production are the main sources of methane in this country. Germans -- with obvious reason -- coined the term "throw-away society" for societies like their own that are generally rich, highly developed economically, and seemingly can afford to throw things away. (Note, however, that Germans have also put in place an advanced, nationwide recycling system.) Livestock production (cattle and hogs) are big in the vanishing agricultural sector.

Ghana: Livestock. Cattle and other ruminants are important in agriculture.

India: Wet rice production and livestock (cattle -- also a symbol of affluence -- and some other ruminants) are top methane emitters. See explanations for India and Ghana.

Japan: Solid waste and livestock are the biggest methane emitters. See the explanations for Germany.

S. Arabia: The comparatively small, top methane emissions are related to the oil and gas production in Saudi Arabia.

USSR: The largest emissions are--as in Saudi Arabia--linked to oil and gas production; secondarily to livestock raising and coal mining.

USA: See the same patterns for Germany and Japan, albeit at a grander scale.

C) What perspectives do you think your country would bring to an International Environmental Conference on GHG emissions? Will your country seek to limit emission reductions or demand reductions from all countries?

Only "rules of thumb" are provided here, which need to be adapted to the individual situations of any country.

- The activity that brings a country most benefits economically and/or politically are the "untouchables" in international negotiations for emission reductions. At least, these are the most difficult to reduce because a country would not easily be willing to give up its major source of income.

- Generally, southern/developing countries aspire to many of the development standards and amenities of northern/developed countries; they argue for their right to industrialize.

- Developed countries are economically in the most able and flexible position to employ more efficient and cleaner technologies, yet they lack the political will to demand lifestyle changes of their people or vast investments by their industries.

- Most developing nations are rich in population and have large population growth figures whereas developed nations have slower population increases but much larger consumption figures (both absolute and in terms of increases). Thus, developed nations like to point out the "population threat" whereas developing nations like to point to the "consumption threat."

## Activity 3.3: Patterns and Trends in Human Activities Producing Greenhouse Gases

**A)** Describe the relationship between total industrial $CO_2$ emissions per capita and GNP per capita.

- The higher the GNP per capita, the higher the total $CO_2$ emission per capita (the relationship might even be non-linear).
- Distinctions between countries seem to be related to the degree of efficiency achieved in a country's economy. Other reasons may include lifestyles, climate, types of industries present, etc. See, for example, US vs. Japan.

**B)** Describe the relationship between total industrial $CO_2$ emissions and total population.

- There is also a general tendency for total $CO_2$ emissions to increase with total population; however, there is a significant spread.
- This spread (variation) may be explained by degree of development and industrialization, access to resources, types of industries present, etc.

**C)** How might these relationships affect international efforts to control GHG emissions?

- Much emphasis will be placed on technological innovation (low-energy needs, the turn away from fossil fuel-based technologies and products, etc.), increasing energy efficiency, and population control.
- The political dominance of developed nations means that negotiations will not give due weight to reducing consumption and lifestyle changes--however important that may be.

**D)** Discuss the trends for the country you have focused on so far, and try to explain short-term variations in emissions.

- Point out to students that it is very difficult and therefore tenuous to assign major economic developments to countries over such a short period as from 1970 to the early 1990s. The indications given below should be interpreted with caution!
- It is common to point to 1973 as the beginning of restructuring in western market economies. This turn can be found in several of the graphs shown.

**Brazil**: The curve describes the development history of Brazil with the decade of the 1970s being the "boom-decade," and the years after that showing the industrial emissions being almost in sync with the global economic recession and growth cycles.

**China**: Increasing population growth, exploitation of its coal resources, and industrialization (more recently advanced with the opening toward western market-oriented economies) are the reasons behind the steady upward trend. Smaller variations hint at 5-year plans, and the political trepidations in China under its various leaders.

**Germany**: The highly variable trend line reflects several developments and events: the ever-increasing industrial output of post-WW II Germany; the oil crises in the mid and late 1970s; the economic depression of the 1980s with an improvement in the late 1980s; legislation (in concert with other European nations in the EU) to increase energy efficiency; and the industry's difficulties and restructuring in the late 1980s and early 1990s, including the enormous pressures put on the German economy following reunification.

**Ghana**: Overall, Ghana's industrial carbon dioxide emissions are at a very low level, a fact that seems to magnify (at this particular scale) the ups and downs of the curve. (These little variations wouldn't even show for, say, the United States!). The steady emissions since the mid-1980s may reflect the quality of the data (*i.e.*, no updated data may be available), rather than a stable/stagnating economy.

**India**: See explanations for China (without the 5-year plan indication). Minor variations in the general upward trend may reflect some of the political instability in India.

**Japan**: Japan's trend also shows the breaks after the oil crises in 1974 and 1978. The volatility of the line may reflect world economic trends underlying periods of economic expansion and trends toward higher energy efficiency.

**Saudi Arabia:** The generally upward trend is the result of world oil demand (and SA's supply response to that demand), and of economic recession and expansion cycles. The slight dip in the early 1990s reflects the influence of the Gulf War.

**USSR**: The former USSR shows much of the same trend as China, with some significant differences: the steep increases in the 1970s; the economic stagnation in the early 1980s; the impacts of Glasnost in the later 1980s; and the economic collapse after 1989-90 as the Eastern block began to fall apart.

**USA**: The trend shows the big oil crisis impact around 1974/75, the stagnation at a high plateau in the late 70s; a major down-turn with the worldwide recession in the early to mid-80s; and some recovery since then.

E) Now examine Figure 8j which plots all nine countries on a single graph. What do you observe when all nine plots are shown on a single plot?

- This graph allows a comparison of emissions among countries while also depicting the overall emission trends over time.
- With regard to the former, we see reflected what the choropleth mapping example also demonstrated--the US is the world's biggest $CO_2$ emitter, followed at somewhat lower rates by other highly developed countries (Germany and Japan) and rapidly developing countries (the former USSR and Saudi Arabia). At the bottom are very populous, but little developed countries such as India, Ghana, Brazil, and (for now) China.

- With regard to the latter, the overall trends, there seems to be a narrowing of the gap between developed and developing countries. Also, the values shown on the y-axis do not pick up the sometimes dramatic upward trends seen in the graphs for each country.
- What this graph hides is the overall picture of total emissions, i.e., what happens when emissions per capita are multiplied with the number of people in a country.

# 4

# International Environmental Policy and Negotiations

## Background Information

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This unit addresses international environmental policy making on climate change. As mentioned earlier, climate change is a problem of global magnitude. Causes, impacts, and responses must therefore be examined and implemented at the global, international scale. A brief introduction on pertinent international law, which is the basis for international negotiations on climate change, is provided. The climate negotiations which took place at the Rio Earth Summit (in 1992) and the Berlin Climate Summit (in 1995) culminated in the Framework Convention on Climate Change (FCCC). This Convention, signed by 167 governments to date, has been negotiated in a participatory process involving world governments (through representation on the Intergovernmental Negotiating Committee, INC), scientists (under the Intergovernmental Panel on Climate Change, IPCC), non-governmental organizations (NGOs), and industry NGOs.

This unit addresses key debates and issues raised during the climate negotiations, including:

- allocating responsibility,
- dealing with varying regional impacts,
- the adequacy of commitments,
- carrying out joint implementation,
- the transfer of technology,
- financing mechanisms, and
- scientific uncertainty.

## International Climate Change Negotiations

### International Law and Climate Change[7]

The UN Framework Convention on Climate Change was adopted in May, 1992 and opened for signature in June at the **Rio Earth Summit**. Conventions or treaties among states are a key source of international law. They set out obligations that are binding on their party states. As a framework convention, the climate treaty contains important principles and general obligations. Additional commitments may be agreed upon later in one or more protocols.

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[7] This section is primarily derived and adapted from information available at the time of writing from the United Nation's Environmental Program's WWW site (http://www.unep.ch/iucc/).

Customary international law also provides some general guidance on the legal implications of climate change. An unwritten international norm becomes part of customary law if it is consistently followed for a long time by a significant number of states that accept it as a legal obligation. For example, if a particular commitment to act is repeatedly expressed at important international conferences, and if all the participating states act in accordance with it, then the commitment may become an obligation under customary law.

Existing customary law affirms the sovereign right of states to manage their own natural resources, although this right is by no means absolute. Customary law also prohibits a state from allowing activities on its territory to inflict serious damage on the environment of other states or on parts of the environment that do not belong to any state. Although states are not prohibited from causing any environmental damage at all, they must make "reasonable use" of common resources such as the atmosphere. The problem is that there is no common agreement on what is "reasonable." Exactly how much carbon dioxide is a state permitted to release into the atmosphere? How much forest may it turn into agricultural or industrial land? Customary law has no definitive answers.

Until 1992, international law did not address climate change directly. Because human-induced climate change is a phenomenon of unprecedented scale and character, traditional legal concepts and mechanisms provided by treaties and customary law do not help much. A number of treaties already in force, notably the Geneva Convention on Long-Range Transboundary Air Pollution and the Montreal Protocol on Substances That Deplete The Ozone Layer, do deal with atmospheric pollution. They do not, however, specifically address the causes and effects of climate change.

Non-binding statements by international climate conferences influenced the drafting of the Climate Change Convention by the Intergovernmental Negotiating Committee for a Framework Convention on Climate Change (INC/FCCC). The treaty drafters referred to the statements to evaluate the concerns and proposals of various states and regions. In this way, a number of concepts and principles were reaffirmed and highlighted. The following three paragraphs describe the most important of these principles:

Climate change is a "**common concern of humankind**." Representing an effort to provide a basis for international action to protect the global climate, this concept was first introduced in a 1988 resolution of the United Nations General Assembly. It has since been supported by numerous international climate meetings. The legal problem is that climate change is not imposed by one state upon another state. As a result, the traditional legal principles governing transboundary pollution (which is imposed by one state upon another) do not apply. But if the atmosphere is a "common concern of humankind," all states have an interest and duty to protect it from serious harm. A state on one side of the globe is thus "affected" by a state on the other side of the globe that is emitting greenhouse gases into the atmosphere. This principle is affirmed in the preamble to the Climate Convention.

States have "**common but differentiated responsibilities**" for combatting climate change. It is widely recognized that all states contribute to climate change and that all states may,

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to different degrees, suffer from it. But the industrialized states developed their economies over the past 150 years in part by treating the atmosphere as a free and unlimited resource, and they continue to generate the greatest quantity of greenhouse gases. Developing countries are now attempting to industrialize at a time when the atmosphere is no longer considered free and unlimited. In addition, they still make a smaller contribution to climate change (although it will increase in the decades to come). The principle of "common but differentiated responsibilities" proposes that, while all states should act to prevent damage to the atmosphere, developed countries should take the lead. This principle is widely recognized. It was incorporated into the 1989 Montreal Protocol and it underlies the dual standard of commitments for developed and developing countries established by the Climate Convention.

Potentially dangerous activities should be restricted or prohibited even before they can be proven to cause serious damage -- a common but contested interpretation of the **precautionary principle**. Traditionally, activities are often not restricted or prohibited by legal rules until they are proven to cause environmental damage. In other words, states commonly are free in their activities unless and until a causal link between an activity and a particular damage is established. This approach may not work, however, in the case of activities contributing to climate change. Scientists are still unsure about the exact timing and nature of climate change impacts, but if efforts to limit net greenhouse gas emissions are not initiated before scientific certainty is achieved, it may be too late to undo the damage. (See also the section on "The Case for Reducing Greenhouse Gas Emissions Despite Scientific Uncertainty" below.)

## The Rio and Berlin Summits and the Climate Convention

The United Nations Framework Convention on Climate Change is the first binding international legal instrument that deals directly with climate change. The Convention was adopted on May 9, 1992, after 15 months of tough negotiations by the UN-sponsored Intergovernmental Negotiating Committee for a Framework Convention on Climate Change (INC/FCCC). It was opened for signature at the **Earth Summit** in Rio de Janeiro the following month, where it was signed by the representatives of 154 states and the EEC (now the EU). By June 19, 1993, when the treaty was closed for signature, 167 states had signed. The 50th ratification was received on December 21,1993, triggering the Convention's entry into force 90 days later on March 21, 1994.

The **Climate Summit in Berlin** in 1995 was the first chance since the Earth Summit for governments who signed and ratified the Framework Convention on Climate Change, or Climate Convention for short, to commit themselves to further reduction of greenhouse gases. Such a commitment would have directly influenced the lives of ordinary people because governments would have to take definite action -- and that could have meant anything from investment in public transport and energy conservation, to energy or carbon taxes. Unfortunately in the minds of many and despite some urgent calls for action,.the Berlin Summit did not yield any further emission reduction commitments--from the developed or the developing countries (World Resources Institute 1996: 322).

## The Groups Involved

The Climate Convention is the result of negotiations among many groups, with input from a variety of interests. The most important are described briefly below.

- Most of the world's governments--167 of them--have signed the Framework Convention on Climate Change (FCCC). Brought together by the United Nations, the Convention is serviced by a small secretariat based in Geneva. Each Government sent negotiators to the **Intergovernmental Negotiating Committee** (INC). At Berlin the INC presided over the first formal meeting of the nations that had ratified the Convention--future meetings will be known as the **Conferences of the Parties** (COP).

- Hundreds of senior climate scientists from around the globe who collaborate in the Intergovernmental Panel on Climate Change (IPCC) regularly come together and produce advisory reports for the INC and in the future for the Conference of the Parties.

- Environmental non-government organizations (NGOs)--including the Climate Action Network (CAN), an umbrella organization of more than 160 NGOs worldwide--have attended all the negotiating sessions to date and continue to lobby their governments at home. They range from large international groups such as World Wildlife Fund and Greenpeace to a host of smaller organizations. There are Climate Action Networks in West and Eastern Europe, North and South America, Africa, and Asia.

- Industry non-government organizations--mainly a lobby on behalf of the fossil fuel industry--have lobbied against the Convention. The most visible group is the Global Climate Coalition, funded by, among others, Amoco, Arco, BP, Shell, and Texaco. Recently, however, the industry lobby has become split, as organizations like the US-based Business Council for a Sustainable Energy Future have become involved. Representing the interests of energy efficiency, conservation, and renewable energy production, this group supports the need for a Climate Convention.

These interest groups bring a variety of goals, perspectives, needs, and biases to the table which has resulted in many challenges, including both obstacles and opportunities, throughout the FCCC negotiations.

## Goals of the Climate Convention

The Convention's ultimate objective is the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous **anthropogenic** interference with the climate system." To achieve this objective (stated in Article 2), the Convention sets out a series of commitments. The adequacy of these commitments will be periodically reviewed in light of the treaty's objective, new scientific findings, and the effectiveness of national climate change programs. As a framework treaty, the Convention sets out principles and general commitments, leaving more specific obligations to future legal instruments. The key principles incorporated in

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the treaty are the **precautionary principle** (see "The Case for Reducing Greenhouse Gas Emissions Despite Scientific Uncertainty" below), the common but differentiated responsibility of states (which assigns industrialized states the lead in combatting climate change), and the importance of sustainable development (Article 3). The general commitments, which apply to both developed and developing countries, are to adopt national programs for mitigating climate change; to develop adaptation strategies; to promote the sustainable management and conservation of greenhouse gas "sinks" (such as forests); to take climate change into account when setting relevant social, economic, and environmental policies; to cooperate in technical, scientific, and educational matters; and to promote scientific research and the exchange of information (Article 4).

The Convention also establishes more specific obligations for particular categories of states. It distinguishes between members of the OECD, countries in transition to a market economy, and developing countries. The Convention requires OECD countries to take the strongest measures, while the states in transition to a market economy are allowed a certain flexibility. The Convention recognizes that compliance by developing countries will depend on financial and technical assistance from developed countries; in addition, the needs of least developed countries and those that are particularly vulnerable to climate change for geographical reasons are given special consideration (Article 4). This approach is consistent with the widely recognized principle of the common but differentiated responsibility of states at different levels of development (see the sections on "Allocating Responsibility" and "Winners and Losers" below). Developed countries and states in transition to a market economy must take the lead in adopting measures to combat climate change. They should take measures designed to limit emissions of carbon dioxide and other greenhouse gases, with the aim of returning to 1990 emissions levels by the year 2000. The differing economic circumstances of these countries are to be taken into account, however, and several states may together adopt a common, joint target (Article 4) (See the "Joint Implementation" section below).

The OECD countries must facilitate the transfer of technology and provide financial resources to developing countries to help them implement the Convention. The Convention requires OECD countries to finance the costs incurred by developing countries for submitting reports on their greenhouses gas emissions and measures for implementing the treaty. This financial assistance is to be "new and additional," rather than redirected from existing development aid funds. In addition, OECD countries are to provide financial resources for other Convention-related projects that are agreed to by both a developing country and the Convention's financial mechanism (see more on "Financial Mechanisms" below). This financial mechanism will initially be administered by the Global Environment Facility, but the Convention's parties could agree in the future to transfer the administration of the mechanism to another international body. As for technology transfer, the Convention does not specify the terms of the transfers, such as whether they should be made on commercial or non-commercial terms (see the "Technology Transfer" section below).

The Convention establishes institutions to support efforts to carry out commitments and to monitor compliance. The Conference of the Parties (COP), in which all states that have ratified the treaty are represented, is the Convention's supreme body. It met for the first time in March

1995 and will meet on a yearly basis thereafter. It promotes and reviews the implementation of the Convention and, if appropriate, adopts amendments, annexes, and protocols (Articles 7 and 15). The Convention's Secretariat provides administrative support and ensures the flow of information among Parties (Article 8); the INC/FCCC Secretariat has provided these services on an interim basis (Article 21). Two subsidiary bodies assist the COP, one for scientific and technological advice and the other for implementation (Articles 9 and 10). The COP can also set up additional bodies if it so decides.

The Climate Change Convention is considered a major step forward by FCCC supporters in the international response to climate change. Much work remains to be done, however. Many states after ratifying the Convention still need to formulate national laws and policies that will enable them to meet their commitments. The COP itself has an enormous amount of work to do to ensure that the Convention is a success in the years and decades to come.

## Key Debates and Issues

Strange as it may sound, as a global natural resource the climate belongs to everyone. No one has the moral right to deny to others the benefits it can bring. But because climate change is likely to do just that, it raises the issue of how various countries should contribute to efforts to reduce global greenhouse gas (GHG) emissions. More to the point, who should finance these efforts? This essentially political question of responsibility can be expressed in a "**responsibility index**," but there is no generally agreed framework for quantifying responsibility in this way (see Unit 3 above). Should the index be based on past, present, or future emissions? Should it include only carbon dioxide, or all greenhouse gases? Should emissions be calculated on a GNP, per capita, or some other basis? Should a country's forests and other carbon dioxide "sinks" be counted as "negative emissions?" Should the uneven impacts of climate change on underdeveloped vs. developed countries and on mid- and high-latitude vs. low-latitude nations be considered in any way? How will technological advances be transferred to countries unable to invest in their development, but likely to experience negative impacts from climate change? All of these are key issues of debate and are dealt with in more detail below.

### Allocating Responsibility[8]

The UN Framework Convention on Climate Change points out that "the largest share of historical and current global emissions of greenhouse gases has originated in developed countries." The developed countries have contributed about 86% of the cumulative world total of fossil fuel-related carbon dioxide emissions to date. But historical emissions occurred in ignorance of the consequences of the greenhouse problem. Are current generations responsible for their country's unwitting mistakes of the past? Policies devised now can only affect present and future emissions, not those of the past. On the other hand, since the developed nations have achieved their prosperity without concern for the build-up of GHGs, why should the developing nations now have to face these extra constraints without international economic assistance?

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[8] This section is primarily derived and adapted from information available at the time of writing from the United Nation's Environmental Program's WWW site (http://www.unep.ch/iucc/).

The Convention also states that emissions of all GHGs are important and should be included in emission reduction plans. Ideally, then, all greenhouse gases--carbon dioxide, methane, nitrous oxide, CFCs, and so on--should be included in a responsibility index. Considering all GHGs as part of one overall reduction target would be cost effective, as making the first, small reductions of each gas would be cheaper than large-scale reductions in just one gas. But this advantage must be balanced against the fact that measuring emissions of methane and some other GHGs is extremely difficult. Because there is much better information about emissions of carbon dioxide, by far the most important greenhouse gas, it would be more practical to develop an index that requires monitoring only $CO_2$ reductions. Countries for whom $CO_2$ emissions form a large percentage of total GHG emissions would be penalized by such an index, whereas those for whom methane (typically developing countries) or CFCs (industrialized countries) are particularly important would benefit.

Current emissions of GHGs can be expressed on either a per country or per capita basis. Since about 55% of current GHG emissions come from the industrialized countries, which contain less than 25% of the world's population, these countries have high per capita emissions. So too do many small oil-producing states and countries with high rates of deforestation. The largest developing countries, though contributing a significant percentage of global emissions, disappear entirely from a list of the 50 largest per capita emitters. The Climate Convention notes "that per capita emissions in the developing counties are still relatively low and that the share of global emissions originating in developing countries will grow to meet their social and development needs." A related issue is whether emissions from activities ensuring basic needs fulfillment should be classified as **survival emissions** (emissions that could not easily be reduced) and those resulting from activities beyond basic need fulfillment as **luxury emissions** (those that could, in principle, be reduced more easily).

As discussed in Unit 3, **scientific uncertainties** about present emissions complicate efforts to allocate responsibility. The main problem concerns natural GHG sources (such as plants and animals) and sinks (notably forests and the oceans). Without a better understanding of these natural processes, it is impossible to be sure that only human-made emissions are being measured. Current data are either specific to local sites and climatic regions or not well documented at all. Data on land use and changes in land use, particularly deforestation in the tropics, are frequently disputed. As a result, it is easier to calculate **gross emissions** than **net emissions** (gross emissions minus absorption by sinks). Despite these problems, the major rankings of GHG emissions are based on $CO_2$ emissions from deforestation and industrial sources, and on methane and CFC-11 and CFC-12 emissions.

Existing rankings reflect these complex scientific and political issues. The best-known rankings are those of the Intergovernmental Panel on Climate Change (IPCC), the World Resources Institute (WRI), and the Centre for Science and Environment (CSE) (see Unit 3). The rankings add up each country's annual emissions of carbon dioxide, methane, and CFCs. WRI and

IPCC differ only over how each gas is "weighted" according to "potency" and atmospheric life time.

Three major groupings of countries have emerged in the negotiating process--the developing South, the industrialized North, and oil- and other fossil fuel-exporting countries. There are splits within these groups, but the fundamental arguments in the negotiations revolve around their priorities; for many observers this is a rich North vs. poor South debate.

## Climate Change: North vs. South, Winners vs. Losers

If we accept the least controversial measure--cumulative fossil-fuel emissions of carbon dioxide (the most important greenhouse gas)--then the contribution of the industrialized countries to climate change can be quantified as being more than 80%. Thus, the industrialized countries of the northern hemisphere must be seen as having contributed the most to changes in the Earth's atmosphere.

Industrialized countries are also better positioned to absorb the negative effects of climate change. With their more diversified industrial economies, richer countries have more resources for responding to climate change. What's more, agriculture in the US, Canada, northern Europe, and Russia may even benefit if global warming leads to longer growing seasons and improved moisture conditions. As a result, the North may prove to be the relative winner vis à vis the South, gaining more from the fruits of industrialization while suffering less from the consequences of climate change. The developing countries of the South on the other hand are the most vulnerable to the likely impacts of climate change. Their economies are often highly dependent on agriculture, which is the economic sector most at risk. The danger is greatest for those countries whose agriculture is already marginal and exposed to droughts and other dangers. Also, because developing countries have weaker economies, they may lack the financial resources necessary for addressing the economic and social consequences of climate change. Certain developing countries would be particularly vulnerable because they are already at the limits of their capacity to cope with problems under current climatic and societal conditions.

As a result, climate change may intensify conflicts between the rich and poor nations of the world. Although caused mostly by 150 years of industrial activity in the North, climate change is likely to have its most destructive impact on the nations of the South, exacerbating existing North-South inequality. Disputes over "**environmental refugees**," **technology transfer**, and financial assistance would further threaten collaboration between the North and the South. Current controversies over who is responsible for causing--and thus perhaps for combatting--climate change are just the first signs of this widening North-South gap.

Some of the key issues specifically related to the North-South debate are:

- Should a country's current or past role in causing climate change determine its share of the costs and sacrifices now needed to minimize it?

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- Should each nation's contribution to climate change be measured only by its emissions of carbon dioxide, or should other greenhouse gases be considered as well?
- Should each country's permitted emissions quota be calculated according to its current emissions level, its population size, or some other measure?
- Who should pay for saving the world's dwindling tropical forests? Deforestation without reforestation has the effect of increasing atmospheric concentrations of $CO_2$.
- Is climate change data, mostly generated in the industrialized countries, free of political bias?

Geographical location will influence how individual countries are affected by climate change. Scientists find it difficult to forecast the regional impacts of climate change. Their global forecasts of rising sea levels, atmospheric warming, and weather instability, however, suggest that countries with coastal and ecologically fragile regions will be the biggest "losers." Countries located at higher latitudes, on the other hand, may actually be climate change "winners," at least in the short term. The impact on agricultural productivity may vary from country to country. In general, warmer weather should increase both growing seasons and crop growth rates, except in areas that already are extremely hot. Agriculture also crucially depends on the quantity of rainfall, its distribution throughout the year, and the amount of moisture remaining in the soil. In many arid and semi-arid regions, rainfall may decline, further devastating agriculture. It is difficult to predict which agricultural zones will be advantaged or disadvantaged by climate change.

Countries with large coastal areas less than one meter above the current sea level are expected to be big losers. These countries include small island states, archipelagos, and coral atoll nations, such as the Maldives, the Marshall Islands, and Tuvalu. While the Netherlands has throughout its history made an enormous investment in protecting its coastline, poorer coastal countries, such as Bangladesh will find coastal protection hard to afford. Countries located partly or entirely in ecologically fragile regions are also at high risk. These regions include arctic and sub-arctic, desert and semi-desert, and high-mountain ecosystems. Their response to climate change would depend in good part on the rate of change. If the climate changes too rapidly, many plant, animal, and insect species will be unable to migrate or adapt. As species die off, these regions would become more prone to soil degradation and ecological simplification and other damage, particularly if climate change also results in more frequent storms.

Poor countries may be the biggest losers of all. If climate change has its predicted impacts, many developing countries may lack the necessary resources for protecting themselves. As a rule of thumb, richer is safer because wealth provides the capacity for flexible responses to unwanted risks, especially when precise understanding of these risks is not available or perhaps not even possible as is the case with global climate change. Climate change may thus widen the gap between rich and poor. If climate change begins to take a heavy toll, countries may perceive each other as winners and losers. Clearly, climate change is not in the long-term interests of any country. Perceived differences in the global distribution of short-term negative impacts would have powerful political implications. So too would an awareness that some countries are more responsible for greenhouse gas emissions than are others. Accusations and conflict could be expected to increase.

## Adequacy of Commitments

In addition to questions of who is responsible for causing climate change, to what extent, and who wins or loses from climate change, there is the question of whether what we do about reducing emissions is actually enough to prevent further warming and potential impacts. After all, warming is more directly linked to greenhouse gas **concentrations** in the atmosphere, rather than **emissions**. The distinction is critical because if we emit at the same rate but eliminate GHG sinks, the concentration in the atmosphere will still continue to rise, increasing the potential for global warming and its impacts.

Article 4 of the Convention concerns global concentration of greenhouse gases, primarily $CO_2$. At present the Convention calls on industrialized countries to aim to return greenhouse gas emissions to 1990 levels by the year 2000. It says nothing about reducing emissions after the year 2000. The IPCC has clearly demonstrated that countries need to reduce global emissions to well below 1990 levels if the concentration of $CO_2$ in the atmosphere is to remain stable. Current commitments to stabilize rather than reduce emissions are clearly inadequate.

The Alliance of Small Island States (AOSIS) protocol calls on industrialized countries to commit themselves to a 20% reduction of $CO_2$ emissions from 1990 levels by the year 2005. This target is known as the Toronto Target. By December 1994 eight industrialized countries had incorporated the Toronto Target, or a target very similar to the 20% by 2005 cut, into their official National Plans. These are: Australia, Austria, Canada, Denmark, Germany, Luxembourg, Slovak Republic, New Zealand. The US does not currently support the Toronto Target because of what it sees as possible impacts on the US economy. At present the official US position is that current commitments are inadequate, but the US is not proposing any remedy to this. Without a firm commitment by industrialized nations to reduce emissions, the Convention's goals may never be realized.

## Joint Implementation (JI)

Article 4 permits nations to meet emissions targets "individually or jointly," but as yet nobody has managed to define what this really means. By providing finance for a project that can help another country reduce its current (or even potential) emissions of $CO_2$, a donor country may include the amount of $CO_2$ saved by that project in their own national $CO_2$ figures. Supporters see this as a mechanism that could attract private capital toward more climate-friendly alternatives, and thus help countries meet their development objectives at the lowest carbon and economic costs. Critics, including many Southern governments and most of the NGO community, argue that Joint Implementation (JI) provides an escape for industrialized countries to take no action at home. A detailed report on JI from a European NGO perspective is available from Climate Network Europe. Even NGOs in the North who see JI as perhaps having a role to play in the

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process are adamant that it should not be used as an escape hatch for industrialized countries to avoid meeting their emissions reductions at home. In general Southern nations broadly oppose JI and say it should take place only among industrialized countries in the North. Industrialized nations generally support the concept, arguing that more emission reduction can be achieved for less expenditure in countries lacking state-of-the-art technology than in developed countries where additional reductions would come at a high price.

## Technology Transfer

Many developing countries, and those of Central and Eastern Europe, realize that their emissions will increase over the coming decades. They want access to the latest technology so that they can increase energy use without necessarily increasing greenhouse gas emissions. To do this the industrialized North will have to provide access to appropriate technology for countries in the South and Central and Eastern Europe -- a politically hot issue as technical advantage usually means an economic advantage. Technology transfer is also a critical issue in relation to the impacts of technology on the societies using them. Often these impacts are profound, and economic benefits come at a high socio-cultural price.

## Financial Mechanisms

Because of the costs associated with implementing the Convention, developing countries agreed to sign it only if developed countries provided additional financing. A financial mechanism should administer funds to pay the costs incurred by developing countries in meeting their commitments. Depending on the activity, the financial mechanism will cover either full or "incremental" costs. "Incremental cost" is a new and not well understood concept. One of the ideas behind it, though, is that it may cost extra to get a global benefit such as reduced greenhouse gas emissions. Developed countries are expected to help pay these extra or "incremental" costs, because they will be sharing the benefits. One or more international institutions such as a United Nations agency or multilateral development bank will administer the financial mechanism. It must have a democratic and transparent decision-making structure and be accountable to the COP for its Convention-related activities. Parties are currently discussing the relationship between the COP and the financial mechanism. The COP will provide guidance on how funds should be used. Guidance so far includes that ideas for activities should originate in recipient countries and, for the time being, priority should be given to reporting and enabling activities such as capacity building, planning, and research.

The **Global Environment Facility** (GEF), operated by the World Bank, United Nations Development Programme (UNDP), and United Nations Environment Program (UNEP), is the interim financial mechanism. Hastily established in 1990, it received much criticism for its focus on the global rather than local environment, its association with the World Bank, the top-down project development, lack of transparency, ill-defined decision-making structure and its US$5 million membership fee. In 1994, toward the end of its three-year pilot phase, the Facility was "restructured" in order to comply with the conditions of the Climate and Biodiversity

Conventions. The GEF is currently in a transitional phase. Environmental groups are waiting to see whether the new structure will be more transparent and implement better projects.

While former East-bloc countries are not eligible for financing under the Convention, they can receive funding from the GEF. Although projects related to adapting to climate change are not within the mandate of the GEF, the Parties and the GEF are seeking ways to provide funding through the Facility.

To date less than US$2 billion has been pledged to the GEF for the period 1994 to 1997, only 40% of which will be used for climate-related activities. By comparison, the World Bank alone will invest ten times that figure in energy and transport projects over the same period. The vast majority of Multi-lateral Development Bank (MDB) financing for energy development promotes fossil fuel use rather than renewables or energy efficiency. There is an obvious lack of consistency between the financial activities of MDBs in general and the objectives of the Climate Convention.

## Reducing Greenhouse Gas Emissions Despite Scientific Uncertainty

Scientific uncertainty over climate change has led some people to doubt the appropriateness for a vigorous policy response. Although most scientists believe that human activities are changing the climate, they do not agree on the rate at which it will occur, nor on its specific impacts. This makes it difficult to put a "price tag" on either climate change or on policies to prevent it. Nevertheless, the seriousness of the potential damage and the availability of cost-effective policies are strong arguments for taking immediate action to minimize climate change. Furthermore, there are so-called win-win strategies that would invest in emission-reduction projects and technologies now, reducing production or use costs today and having the positive side effect of limiting global warming, saving money in the future.

Action is necessary because the damage caused by climate change is potentially catastrophic and irreversible -- at least for some. Estimates of the probable damage from climate change vary widely, from moderate to overwhelming. If the Earth's surface warms by several degrees centigrade over the next 100 years as predicted, it seems clear that millions of people would be vulnerable to the effects of famine, drought, coastal flooding, and more. Nasty surprises, such as changes in major ocean currents that strongly influence regional weather patterns, could not be ruled out. If such disasters started to occur, it would take at least several generations before measures to reverse climate change could have significant results. The money spent on taking action now could be viewed as an insurance premium for protection against a hard-to-measure but potentially devastating risk.

The first cuts in greenhouse gas emissions would be relatively cheap. Some 10% of emissions could be eliminated by raising industrial and energy efficiency and by removing counter-productive policies, such as subsidies for clearing forests. The longer such steps are delayed, the more expensive it will become to achieve identical results with future policies.

Furthermore, by the time these early reductions are completed and more expensive decisions must be made, the scientific evidence concerning climate change should be clearer.

Reducing greenhouse gas emissions would have additional benefits unrelated to climate change. Fuel efficiency would save money. Lower emissions of pollutants from factories and automobiles would improve air quality in urban centers and reduce acid rain. Putting a stop to deforestation would reduce soil erosion, offer aesthetic and economic benefits, and protect biodiversity and subsistence forest dwellers. One study suggested that while a hypothetical carbon tax might cost Norway 2.75% of its **Gross National Product** (GNP) in the year 2010, 70% of that cost would be recouped through such non-climate benefits (see UNEP Fact Sheet 230 available at UNEP's WWW-site).

# 4

# International Environmental Policy and Negotiations

## Instructor's Guide to Activities

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### Goal

The activities associated with this unit are intended to demonstrate the challenges the global community faces in responding to greenhouse gas emissions and climate change.

### Learning Outcomes

After completing the activities associated with this unit, students should:

- understand the major greenhouse gas issues and the relevant terminology
- have a grasp of the varying perspectives on global responses to climate change
- know the range of potential responses to climate change and the likely results of those responses

### Choice of Activities

It is neither necessary nor feasible in most cases to complete all activities in each unit. Select activities that are most appropriate for your classroom setting and that cover a range of activity types, skills, genres of reading materials, writing assignments, and other activity outcomes. For this unit, the following activities are offered:

| | |
|---|---|
| 4.1 Role Play--Pro/Con Debate | --role play and debate on the role of the US in slowing global climate change |
| 4.2 Role Play--Rio Conference Simulation | --role play of international perspectives on responding to global climate change |

### Suggested Readings

The following readings are suggested to accompany the activities for this unit and to supplement the *Background Information*. Choose those readings most appropriate for the activities you select and those most adequate for the skill level of your students.

- Unit 4: International Environmental Policy and Negotiations (provided)
  The background information to Unit 4 (all students should read)
- "Are Aggressive International Efforts Needed to Slow Global Warming?" - Yes position by R.E. Benedick, No position by S.F. Singer, in: *Taking Sides: Clashing Views on Controversial Environmental Issues*, T.D. Goldfarb, ed., 6th ed., 308-327. Guilford, CT: The Dushkin Publishing Group, Inc.
- Hammond *et al.* 1991. Calculating National Accountability for Climate Change. *Environment* 33: 11-35. And Commentary, *Environment* 33 (1): 179-185. (provided)

- Understanding Climate Change: A Beginner's Guide to the U.N. Framework Convention (*Appendix C* of this module)

## Activity 4.1 Role Play–Pro/Con Debate

### Goals

In this activity, students will confront the major themes and controversies in the international debate over global warming. Specifically, students will debate whether the United States should take aggressive action to slow global warming.

### Skills

- ✓ role playing (role identification and enactment)
- ✓ identification of major greenhouse gas issues and relevant terminology

### Material Requirements

- suggested readings (most are provided)
- WRI data tables and figures (Tables 5-7 and Figures 6-8j used in Activities 3.1, 3.2, and 3.3)

### Time Requirements

minimum of 1 class period (50 minutes); students may need time to prepare before class

### Tasks

Activities 4.1 and 4.2 are role play simulations conducted by small groups of students as in-class debates. Students will take on the roles of interest groups in activity 4.1 and countries in activity 4.2. As instructor, your role is to serve as moderator and discussion guide. Choose either activity, but it is not necessary to do both as role play simulations. For the activity that you do not select to carry out as a role play, have students write a one to two page paper presenting a particular party's perspective.

For Activity 4.1, assign one of the following interest groups to each group of students:

- Pro scientists/IPCC members
- Con scientists/skeptics of climate change
- Environmental NGOs
- Industrial NGOs
- Loggers
- Farmers
- Miners
- Corporate managers
- Working-class American
- Poor urban American
- Middle/upper-class American

Students assigned to the same roles should spend about 10 minutes prior to debate reviewing their class notes from previous classes and trying to define their position. Discussion will begin with the moderator welcoming participants to the conference. Each delegation will make a 2-minute statement. Once all opening remarks are completed, the moderator will ask individual interest groups to respond to the demands of other participants.

In deciding a course of action to mitigate global warming, students should keep in mind issues relevant to their respective interest groups in terms of the following:

*Prevention* -- options to prevent release of greenhouse gases:

- energy efficiency
- alternative sources of energy
- slowing deforestation

*Mitigation* -- compensating for emissions that do occur:

- reforestation
- "cooling" aerosols (e.g., sulfur dioxide)

*Adaptation* -- helping communities and nations adapt to changes in:

- climate and their consequences
- conservation of biodiversity
- genetic engineering
- coastal developments

*No response* -- take no action to prevent human-induced climate change because:

- scientific uncertainty is too great
- other countries are more responsible and should act first
- free-rider (I'll let others act and go along for the ride without having to do anything myself)
- cannot afford to respond because of impact on economy

If you have internet access, you may also have students search the World Wide Web using the Policy Instruments Database. Information on this database and instructions for accessing it are in *Appendix A* of this module.

After about 20 minutes of debate (not including each group's statement), end the discussion and ask students to reflect on the role play: what was hard? What did they learn? Given their difficulties and opportunities, what do they think are the future prospects for finding a national consensus on the debated issues?

## Activity 4.2 Role Play--Rio Conference Simulation

### Goals

In this activity, students will confront the major themes and controversies in the international debate over global warming.

### Skills

- ✓ role playing (role identification and enactment)
- ✓ identification of major greenhouse gas issues and relevant terminology

### Material Requirements

- suggested readings (most are provided)
- WRI data tables and figures (Tables 5-7 and Figures 6-8j used in Activities 3.1, 3.2, and 3.3)

### Time Requirements

minimum of 1 class period (50 minutes); students may need time to prepare before class

### Tasks

Activities 4.1 and 4.2 are role play simulations conducted by small groups of students as in-class debates. Students will take on the roles of interest groups in activity 4.1 and countries in activity 4.2. As instructor, your role is to serve as moderator and discussion guide. Choose either activity, but it is not necessary to do both as role play simulations. For the activity that you do not select to carry out as a role play, have students write a one to two page paper presenting a particular party's perspective.

For Activity 4.2, assign one of the following countries to each group:

- Brazil
- China
- Germany
- Ghana
- India
- Japan
- Russia
- United States
- Saudi Arabia

Students assigned to the same roles should spend about 10 minutes prior to debate reviewing their class notes from previous classes and trying to define their position. Discussion will begin with the moderator welcoming participants to the conference. Each national delegation will make a 2-minute statement. Once all opening remarks are completed, the moderator will ask individual nations to respond to the demands of other participants.

In deciding a course of action to mitigate global warming, students should keep in mind issues relevant to their respective countries in terms of the following:

*Prevention* -- options to prevent release of greenhouse gases:

- energy efficiency
- alternative sources of energy

- slowing deforestation

*Mitigation* -- compensating for emissions that do occur:

- reforestation
- "cooling" aerosols (e.g., sulfur dioxide)

*Adaptation* -- helping communities and nations adapt to changes in:

- climate and their consequences
- conservation of biodiversity
- genetic engineering
- coastal developments

*No response* -- take no action to prevent human-induced climate change because:

- scientific uncertainty is too great
- other countries are more responsible and should act first
- free-rider (I'll let others act and go along for the ride without having to do anything myself)
- cannot afford to respond because of impact on economy

If you have internet access, you may also have students search the World Wide Web using the Policy Instruments Database. Information on this database and instructions for accessing it are in *Appendix A* of this module.

After about 20 minutes of debate (not including each group's statement), end the discussion and ask students to reflect on the role play: what was hard? What did they learn? Given their difficulties and opportunities, what do they think are the future prospects for finding a national consensus on the debated issues?

# 4

# International Environmental Policy and Negotiations

## Student Worksheets

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### Activity 4.1 Role Play—Pro/Con Debate

**Introduction**

In this exercise you will confront the major themes and controversies in the international debate over global warming. Because global warming is a *global* environmental issue, scientists believe that effective measures to curb emissions must come from international agreements. To achieve this goal, policy makers have devised various schemes that rank national emissions relative to other countries. These guidelines are meant to help negotiators determine national accountability for greenhouse gas emissions and assess to what degree a country should be expected to cut their emissions.

Given the scientific uncertainties of predicting climate change and the considerable economic costs of curbing emissions, there is little agreement over the best course of action to take. Your challenge will be to address some of these issues in a class simulation of a debate about whether the United States should take aggressive and immediate action to slow global warming. Through debate and discussion, you will learn about the following issues related to estimating emissions and responsibility:

1. *The relative importance of different greenhouse gases and the activities that produce them.*

2. *Who should take more responsibility: industrial nations with long histories of emissions, or developing nations with the most rapid increases in rates of emissions owing to population growth and industrialization of their economies?*

3. *Should industrial nations pay for the cost of reducing emissions in the Third World?*

**Instructions**

You have been assigned to play one of the following roles:

- Pro scientist/IPCC member
- Con scientist/skeptic of the global climate change issue
- Environmental NGO
- Industrial NGO
- Logger
- Farmer
- Miner
- Corporate Manager
- Working-class American
- Poor urban American
- Upper-class American

There may be several students assigned to the same role. Find each other and discuss what position you will take in the debate that will follow. Here is the debate question:

**Should the United States take aggressive and immediate action to slow global warming?**

Your instructor will serve as moderator and guide the discussion. Each group will be responsible for answering the debate question based on familiarity with background readings and preparation of a two-minute opening statement to address:

- current greenhouse gas emission levels
- activities tied to emissions
- contribution of each activity to total global emissions
- proposed areas of reduction
- standards you expect other regions to meet
- how global warming threatens the US (*i.e.*, economic, social, and/ or ecological implications of climate change)

After every constituency has made its two-minute statement, you are asked to address other groups' concerns, criticisms, capabilities, responsibilities, and questions.

# Student Worksheet 4.2

## Activity 4.2 Role Play--Rio Conference Simulation

### Introduction

In this exercise you will confront the major themes and controversies in the international debate over global warming. Because global warming is a *global* environmental issue, scientists believe that effective measures to curb emissions must come from international agreements. To achieve this goal, policy makers have devised various schemes that rank national emissions relative to other countries. These guidelines are meant to help negotiators determine national accountability for greenhouse gas emissions and assess to what degree a country should be expected to cut its emissions.

Given the scientific uncertainties of predicting climate change and the considerable economic costs of curbing emissions, there is little agreement over the best course of action to take. Your challenge will be to address some of these issues in a class simulation of an international negotiating forum to limit greenhouse gas emissions. Through debate and discussion, you will learn about the following issues related to estimating emissions and responsibility:

1. *The relative importance of different greenhouse gases and the activities that produce them;*
2. *Scientific uncertainty in measuring emissions;*
3. *The political dimensions of designing regulations to curb emissions and assigning responsibility;*
4. *The driving forces of emissions (for example, population growth, energy consumption, etc.);*
5. *Who should take more responsibility: industrial nations with long histories of emissions, or developing nations with the most rapid increases in rates of emissions?*
6. *Should industrial nations pay for the cost of reducing emissions in the Third World?*

### Instructions

Your instructor will divide you into small groups, each representing one of the following countries:

- Brazil
- China
- Germany
- Ghana
- India
- Japan
- Russia
- United States
- Saudi Arabia

Your instructor will serve as moderator and discussion guide. Each group will be responsible for the following:

1) Familiarity with background readings

2) Preparation of a two-minute opening statement to address:

- current greenhouse gas emission levels
- activities tied to emissions
- contribution of each activity to total global emissions
- proposed areas of reduction
- standards you expect other regions to meet
- how global warming threatens your country (*i.e.*, economic, social, ecological implications of climate change)

NOTE: Use the WRI data used in previous units (see Activities 3.1, 3.2, and 3.3) to prepare your opening address.

3) Prepare additional notes to address the following potential topics:

- the radiative potentials of each greenhouse gas
- problems associated with estimating emissions
- atmospheric longevity of each greenhouse gas
- should historical emissions be taken into account?
- "luxury" vs. "survival" emissions
- driving forces of emissions in different regions
- criticisms of WRI's Greenhouse Gas Index

After every country representative made his/her two-minute statement, you are asked to address other countries' concerns, criticisms, capabilities, responsibilities, and questions. Refer to your notes if it helps you.

# 4 International Environmental Policy and Negotiations

## Answers to Activities

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**Activity 4.1: Role Play - Pro/Con Debate**

and

**Activity 4.2: Role Play - Rio Conference Simulation**

No particular answer key is provided here as these activities are highly subjective and depend on students' choices of roles and role enactment. Take notes on the clarity and content of each representative's opening statement. Students' statements and contributions to the debate should integrate what they have learned from this and previous units.

You may also want to note the students' ability to engage in the discussion in a critical yet respectful manner. If the debate slips into political name-calling, point this out to students in the debriefing period after the role play.

# 5

# Some Solutions to Global Warming

## Background Information

After pointing out all of the uncertainty involved in global climate change and the difficulties in developing international responses, let's turn our attention to some strategies that may help prevent further climate change and mitigate impacts. This unit addresses what we in the industrialized world can personally do to prevent and mitigate the effects of further climate change.[9]

Industrialized countries have many opportunities to reduce $CO_2$ emissions. The Toronto Target is attainable: what is required is the political will to tackle the climate problem through a variety of strategies. Below, we discuss some of these.

## Energy Efficiency

Energy efficiency describes the amount of energy we need to consume a product or to accomplish a task. The UK government estimates that about 20% of total energy production in the UK--in financial terms in excess of 10 billion pounds sterling (US$15.25 billion) per year--is "wasted" (*i.e.*, lost to inefficient energy usage). Between 1973 and 1986 many industrialized countries improved overall energy efficiency by 2 to 3.5% per year, mainly as a response to the increase in oil prices. To maintain this momentum, domestic government policies should include:

- energy and $CO_2$ taxes that would make high-energy use economically unattractive;
- least-cost planning in the energy sector, which given that buying energy is the largest cost factor, will force energy producers to avoid energy losses as much as possible; and
- minimum efficiency standards for appliances, buildings, vehicles, lighting, and industrial motors; such standards would be an incentive to develop and use energy-efficient technology.

The Multi-lateral Development Banks (MDBs) could play a crucial role in the South and in Central and Eastern Europe when it comes to energy efficiency. Over the last ten years, however, less than 1% of energy loans from the World Bank have gone to energy efficiency projects.

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[9] This section is adapted from information available at the time of writing from the Climate Action Network's WWW site (http://www.woodwind.com/imaja/Change/environment/can/can.html).

Improving energy efficiency reduces the "need" to produce more energy--from any source--and therefore reduces greenhouse gas emissions.

## Energy Production

Renewable energy, which includes solar, wind, water (hydro-electricity and wave power), geothermal and biomass (plant based fuels), is still regarded by many governments as a curiosity. Among industrialized nations 74% of government research and development funding over the last 12 years has gone to fossil fuels and nuclear power. Despite this lack of investment, renewable energy has already proven itself to be a viable option in many countries and regions. In California, for example, wind energy already provides enough power to support a city the size of San Francisco. In 1992 the United Nations Solar Energy Group for Environment and Development estimated that about 50% of energy supplies worldwide could come from cost-effective renewable sources by the year 2050.

## Employment

An increasing number of studies in the United States show that, dollar for dollar, investing in energy efficiency is not only more profitable; it also creates more jobs than simply investing in more energy production capacity. In 1992, for example, the US-based Goodman Group analyzed the investments of US electricity companies. They found that energy efficiency generated approximately twice the level of employment in terms of the number of jobs created per million dollars of expenditure, than investing in new gas supply.

Work in the UK by the Association for the Conservation of Energy estimates that a ten-year, 15 billion pounds sterling (US$22.875 billion) investment program to improve energy conservation could create 500,000 jobs. This would significantly cut $CO_2$ emissions (the UK would not have to generate so much energy) and would result in fuel savings of more than 2 billion pounds sterling (US$3.05 billion) over the same period.

A recent study by the German Economic Research Institute on the potential impacts of an energy tax concluded that, not only would there be no negative effects on the economy as a whole, but over a ten-year period 600,000 new jobs would be created.

## Transport

Motor vehicles account for approximately 25% of global carbon emissions, and the vast majority of this comes from industrialized nations. Take an average car used in an industrialized country over its ten-year life span--driven 13,000 km per year, fitted with a three-way catalytic converter and consuming 10 liters of gasoline per 100 km (approximately 29 miles per gallon)--it will produce 44.3 tons $CO_2$. When production and scrapping of the car are included, this increases to 59.7 tons of $CO_2$.

Freight transported in 40-ton trucks produces five times more $CO_2$ per ton per km than if it were moved by rail. Still, road freight within Europe is predicted to grow between 40% and 70% over the next 20 years. A number of policies there combine to make rail transport increasingly unattractive.

Many options have already been tested, including making public transport more available and more affordable; shifting taxes from labor to energy and $CO_2$; least-cost planning; adjusting taxes so they discourage rather than promote private car use; shifting freight transport back onto trains; controlling land use planning so that the need for movement of people or goods is minimized. As with all the other sections above, the money can be found by re-allocating budgets--there may well be no need to find "new" money for such investment. The UK government, for example, plans to spend 18 billion pounds sterling (US$27.45 billion) on expanding its major road network, while the rail network is in the process of being privatized, and subsidies are being cut.

## What Can You Do To Lower Emissions?

Although climate change is a complex global issue, there are things you can do as an individual to minimize the extent of climate change. After all, everyone of us participates in fossil fuel combustion (e.g., by driving cars and other motorized vehicles, or using electricity that was produced from coal), waste production, and the usage of items that are produced with high energy input (most agricultural products, paper, plastic bags, and synthetic fabric, etc.). The first and most important action you can take is to decrease energy use which will directly reduce carbon dioxide emissions. Some actions that will assist in reducing personal energy consumption include carpooling, driving less, insulating your apartment or home, and choosing an automobile that gets good mileage. Replacing old appliances with more efficient models will also result in reduced energy use.

Less effective, but still important actions you can take include simply turning off the lights and appliances when they are not in use. Also helpful are planting trees, which will sequester $CO_2$, keeping the thermostat lower in winter and higher in the summer, and recycling. These steps are considered "less effective" because they contribute less to the overall US economy than does large-scale, industrial fossil fuel combustion. You, as an individual, can affect those larger processes, however, by wise choices of products, and being active in the political arena by pushing governments toward more energy-efficient policies and regulations.

If the average US citizen employed all of these actions, carbon dioxide emissions would be reduced by about 25% or just about 5 tons per year per person (Morgan and Smuts 1994: 7).

# 5 Some Solutions to Global Warming

## Instructor's Guide to Activities

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### Goal

The goal of the activities in Unit 5 is for students to identify responses they can make to reduce GHG emissions and to locate sources of information in the community regarding GHG emission reduction.

### Learning Outcomes

After completing the activities associated with this unit, students should be able to:

- understand the ways in which their personal activities contribute to GHG emissions
- identify ways to reduce their personal contribution to GHG emissions
- write a professional letter to a company or organization that is responsible for GHG emissions

### Choice of Activities

It is neither necessary nor feasible in most cases to complete all activities in each unit. Select activities that are most appropriate for your classroom setting and that cover a range of activity types, skills, genres of reading materials, writing assignments, and other activity outcomes. For this unit, the following activities are offered:

| | | |
|---|---|---|
| 5.1 | Identifying Individual Actions to Control GHGs | --brainstorming, short-answer questions |
| 5.2 | Contacting Individuals and Agencies Involved with GHGs | --team work, investigation, letter writing, group discussion |

### Suggested Readings

The following readings are suggested to accompany the activities for this unit and to supplement the Background Information. Choose those readings most appropriate for the activities you select and those most adequate for the skill level of your students.

- Unit 5: Some Solutions to Global Warming (provided)
  The background information to Unit 5 (all students should read)
- DeCicco, Cook, Bolze and J. Beyea. 1990. *$CO_2$ Diet for a Greenhouse Planet: A Citizen's Guide for Slowing Global Warming*. New York: National Audubon Society.
- Udall, J.R. 1989. "Turning down the heat." *Sierra*, July-August 1989: 26-33.

## Activity 5.1 Identifying Individual Actions to Control GHGs

### Goals

In this activity, students will identify activities that contribute to GHG emissions and consider those over which they have some control. Students will examine ways in which they can reduce their personal contribution to GHG emissions.

### Skills

✓ applying abstract, global knowledge to personal behavior
✓ critical thinking and analysis

### Material Requirements

- suggested readings (some provided)
- Activity 5.1 Student Worksheet
- Personal Energy Log from Activity 2.2 (optional)

### Time Requirements

30-45 minutes

### Tasks

Students are encouraged to brainstorm about their current activities and what they can do to reduce their production of GHG. If you did Activity 2.2, the Personal Energy Log, you may ask students to recall what they learned there. It will raise their awareness again for their own contributions to the greenhouse effect.

## Activity 5.2 Contacting Individuals and Agencies Involved with GHGs

### Goals

The purpose of this activity is for students to engage as activists working in small investigative groups. Students will contact organizations or companies that are in some way responsible for GHG production and investigate what that agency is doing to curb or reduce emissions.

### Skills

✓ critical thinking and analysis
✓ writing professional letters
✓ group oral presentations and discussion

### Material Requirements

- Activity 5.2 Student Worksheet (provided)
- suggested readings (some provided)

### Time Requirements

10 minutes to introduce activity and additional time for students to present and discuss their finding with the class at a later date; students will need additional time for work outside of class

### Tasks

Activity 5.2 is launched with Udall's last suggestion to write local, state, and federal elected officials and advocate emission control programs and increased funding for scientific research into alternative energy sources. Divide the class into "Investigative Units (IUs)." The number of students and sources discovered will determine the size of each IU, but we suggest keeping the number to no more than three students per IU.

Ask each IU to investigate one of the sources listed in Activity 5.1 for information on GHG production. The IU will write a letter of introduction and/or call an agency, organization, or company of their choice that is in some way "responsible" for GHG production (by their assigned source). Have the IU inquire as to what the organization knows about GHGs and how much it contributes to GHG emissions and what it may be doing to curb or reduce emissions. Also have the IU ask what the applicable local, state, and federal regulations are with which that source must comply. If possible, have the IU "double-check" the information they are given by a trip to the library. Ask each IU to present their findings to the class and encourage the rest of the class to ask questions, compare experiences, and debate the findings

# 5

# Some Solutions to Global Warming

## Student Worksheets

### Activity 5.1 Identifying Individual Actions to Control GHGs

**Introduction**

As you have seen in this module, there are many dimensions and scales at which to analyze, predict, and curb the emissions of greenhouse gases. Consider the following list of activities, products, etc. that produce GHGs; some of them will be familiar to you because you have encountered them previously in this module.

*Cement production*
*Refrigerators*
*Foam products*
*Rice production*
*Cattle grazing*
*Deforestation*
*Burning fossil fuels*
*Termites*

Of course, this list is a partial one. Take some time to brainstorm, based on your own experience and what you have learned thus far, to see whether you can add more activities, products, and so on that you think are GHG producers.

**Questions**

A) List additional items that are GHG producers:

B) Now, which of all these activities do you have some degree of personal control over? How would you be able to exert that control? (In other words, how can you reduce your production or emission of GHG?)

# Student Worksheet 5.2

## Activity 5.2: Contacting Individuals and Agencies Involved with GHGs

**Introduction**

In the suggested reading by J.R. Udall, you will find a checklist of things we can do to curb emissions. These include:

- ✓ Use alternative modes of transportation such as carpooling, bicycling, walking, or taking public transport;
- ✓ When you must purchase a new appliance, choose one with energy-saving and energy-efficient features;
- ✓ Although CFCs will be eliminated from refrigerants in the US soon, they are found in items such as foam packaging -- try alternatives!
- ✓ Increase the energy efficiency of your home; many home builders and hardware stores can offer suggestions. Even some utility companies will now assess your household's energy efficiency and suggest remedies. This, in turn, will save you money in the long run, and the atmosphere some carbon dioxide;
- ✓ Reduce, reuse, recycle as many consumer products as possible;
- ✓ Participate in civic tree-planting programs and plant more trees around your home. An average tree will recycle about 50 pounds of carbon dioxide a year;
- ✓ An often-cited but seldom-used action you can take is to write your local, state, and federal elected officials and advocate emission control programs and increased funding for scientific research into alternative energy sources.

**Instructions**

In this activity, we consider Udall's last suggestion. Your instructor will divide you into "Investigative Units (IUs)" with no more than three students in each one. You will work with your IU to investigate one of the sources listed above for information on GHG production. Working with your IU, your group will write a letter of introduction and/or call an agency, organization, or company of your choice that is in some way "responsible" for GHG production. Your IU will contact leaders in the organization to find out what they know about GHGs, the extent of their organization's contribution to GHG emissions, and what it may be doing to curb or reduce emissions. Your IU will also ask what the applicable local, state, and federal regulations are with which that source must comply. Your IU may need to "double-check" the information you are given in the library.

Your IU is responsible for presenting the group's findings to the class and encouraging the rest of the class to ask questions, compare experiences, and debate your findings.

5

# Some Solutions to Global Warming

## Answers to Activities

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### Activity 5.1: Identifying Individual Actions to Control GHGs

**A)** Some examples include:
- hog raising
- waste (decomposition)
- wood fires
- flooding or previously dry land
- plastic bags and other plastic items
- draining of previously flooded land
- as subtypes of fossil fuel burning: electricity production, driving cars, etc.

**B)** This is a judgment call. Students should become aware, however, that they have a choice over the products they buy, the number of times they use these, to some degree also the mode of transportation they use, the political choices they make (which indirectly influence environmental politics, etc.

### Activity 5.2 Contacting Individuals and Agencies Involved with GHGs

No answers provided here as the activity depends entirely on the choices students make, the organizations or companies they will investigate, and the options that they see with each one.

# Glossary

Note: Terms that appear in **bold** in the right hand column are explained elsewhere in this glossary.

| | |
|---|---|
| **absorption** | The process by which the electromagnetic spectrum is selectively weakened as it passes through a medium. This medium takes up the energy and transforms it into a different form of energy. |
| **anaerobic** | Oxygen-free environment, as opposed to an aerobic environment. Decomposition of organic material in an anaerobic environment produces methane gas. |
| **anthropogenic** | Human induced; for example, the anthropogenic **greenhouse effect** refers to the alteration of the composition of the Earth's **atmosphere** as a result of human actions like fossil fuel burning, emission of CFCs, etc.. |
| **atmosphere** | The gaseous mass surrounding the Earth, made up mainly of nitrogen ($N_2$), oxygen ($O_2$), and a variety of trace gases ($CO_2$, CO, $CH_4$, $O_3$, etc.). The lower part of the atmosphere is called troposphere (up to 8-14 km), the part above that is the stratosphere (up to 50 km). The upper part of the stratosphere is the ozone layer. |
| **Berlin Climate Summit** | UN-sponsored international climate conference (1995) attended by governments, which signed and ratified the **Framework Convention on Climate Change**; the Summit presented an opportunity for further commitments to **greenhouse gas** reduction, but few were made. |
| **carbon cycle** | Carbon has a natural cycle on Earth; it is emitted by volcanoes and sea floor vents and absorbed by plants during photosynthesis and stored in tree trunks and other living material and in plant debris in soil. Carbon gas is also present in the **atmosphere** and temporarily taken up by coral and other ocean organisms. |
| **carbon dioxide ($CO_2$)** | A naturally occurring gas, also emitted, e.g., in the process of burning **fossil fuels** such as coal or petroleum. $CO_2$ emissions have grown exponentially over the past decades and are accumulating in the Earth's atmosphere. This accumulation is tied to the enhanced (also known as **anthropogenic**) **greenhouse effect** and probably to the observed warming trend of the past century. |

| | |
|---|---|
| **carbon equivalents** | A combination of indices of the emissions of various greenhouse gases at the regional and national scale based on their **radiative potential**, **residence time**, and other factors. |
| **carbon sinks** | Refers to those components of the **carbon cycle**, like the atmosphere, oceans, and land plants that "take up" **carbon dioxide**. |
| **chlorofluorocarbons (CFCs)** | A compound used in refrigerants, air conditioners, aerosol sprays, etc. that is released into the atmosphere and contributes to the destruction of **stratospheric ozone**. |
| **condensation** | Process by which a substance changes from a gaseous state (such as water vapor) to liquid (water) state. |
| **emission coefficient** | A compound index of what and how much gets released/emitted when burned (including $CO_2$, $CH_4$, $SO_2$, $NO_X$, etc.). |
| **enteric fermentation** | Process by which plant matter is converted by bacteria and other microbes in an animal's digestive tract into nutrients such as sugars and organic acids, producing by-products such as methane, which is released as gas into the atmosphere. |
| **environmental refugees** | People who emigrate from their home region or country because environmental degradation there either harms them physically or prevents them from sustaining their livelihoods. |
| **evaporation** | Process by which a liquid or solid changes into the vapor or gaseous state. |
| **feedback loop** | Reciprocal effect in a system whereby a change in one variable influences changes in other variables, which in turn influence the initiating variable by either reinforcing the tendency of the system to change (positive feedback) or dampening it (negative feedback). |
| **fossil fuels** | Hydrocarbon compounds like crude oil, natural gas, and coal that are derived from the accumulation of plant and animal remains in ancient sedimentary rocks and used as the major energy source of the 20th century. |
| **Framework Convention on Climate Change (FCCC)** | International (UN-sponsored) agreement negotiated in a participatory process and signed by over 165 governments with the ultimate objective of stabilizing atmospheric greenhouse gas concentrations at a level that would prevent dangerous, human-induced interference with the climate system. |

| | |
|---|---|
| **glacial period** | A period during which a continental or mountain ice mass or ice sheet (glacier) advances to cover a formerly ice-free area. A period during which a glacier retreats is known as an **interglacial period**. |
| **global warming** | Increase in average global temperatures; the term is used today to refer to temperature increases that are thought to be caused by human activities enhancing the atmospheric **greenhouse effect**. |
| **greenhouse effect** | Refers to the role of various trace components of the atmosphere (such as $H_2O$, **$CO_2$**, etc.) in reabsorbing certain wavelengths of the energy spectrum radiated from the Earth's surface and thereby increasing the global temperature. This effect occurs naturally, but is augmented by human activities such as burning of **fossil fuels** and land cover changes since these changes emit trace gases that become further concentrated in the atmosphere (enhanced greenhouse effect). Humans have also added a new class of **greenhouse gases: the CFCs**. |
| **greenhouse gases** | Refers to a group of gases, including **carbon dioxide**, **methane**, **chlorofluorocarbons**, **ozone**, and **nitrous oxide** that are radiatively active, i.e., they absorb **longwave radiation** in the atmosphere. |
| **gross emissions** | Total **greenhouse** gas emissions from natural and human-made sources. |
| **Gross National Product** | The total value of all goods and services produced by a nation per year. |
| **interglacial period** | A period of temporary warming and reduction of glaciers between **glacial periods**. |
| **longwave radiation** | Also known as infrared or thermal radiation (heat); the portion of the energy spectrum that is typically reflected and radiated back into space. Longwave radiation is trapped in the **atmosphere** by **greenhouse gases**. |
| **luxury emissions** | Emissions resulting from consumption that could be considered a luxury (as opposed to consumption needed for basic needs fulfillment/survival) (Compare **survival emissions**). |
| **methane** | Naturally produced gas through **anaerobic** processes like those occurring in swamps and bogs. |

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| **missing sink** | Scientific field observations indicate that the oceans take up about half of the carbon in the **carbon cycle**; the rest of the **carbon sink** is in question and referred to as the "missing sink." |
| **net emissions** | Gross emissions minus **absorption** by sinks (forests and oceans) and natural sources (such as plants and animals). |
| **nitrous oxide** | Naturally occurring gas in soils and air, with human sources including fossil fuel combustion, burning of forests, and use of fertilizers. |
| **ozone layer** | A region in the upper stratosphere in which the concentration of ozone ($O_3$) is particularly high. This layer is crucially important in enabling the existence of life because it absorbs harmful incoming ultra-violet radiation. |
| **parts per billion** | Abbreviated ppb(v), refers to parts per billion (volume) units; e.g., mg/ton. |
| **parts per million** | Abbreviated ppm(v), refers to parts per million (volume) units; e.g., g/ton or mg/g (1ppm = 1000ppb). |
| **precautionary principle** | The common but contested notion that potentially dangerous activities should be restricted or prohibited even before they can be proven to cause serious damage. |
| **radiative potential** | A measure of the effectiveness of a gas in trapping **longwave radiation**. |
| **reflection** | Scattering effect of the sun's energy into space by clouds, particles, and light colored land surfaces; when the sun's energy enters the atmosphere about 30% is reflected or scattered back into space. |
| **residence time** | The amount of time a gas remains in the **atmosphere**. |
| **responsibility index** | A measure that would indicate a country's annual contribution to the total amount of global GHG emissions; such measures are sought as a basis to hold nations financially accountable for preventative or remedial measures against **global warming**. |
| **Rio Earth Summit** | Largest UN-sponsored international conference on the environment held in Rio de Janeiro, Brazil, in 1992 at which several international treaties, including **the Framework Convention on Climate Change** were opened for signature. |

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|---|---|
| **ruminants** | Any of a suborder of even-toed, hoofed, herbivorous mammals which chew the cud and have a stomach with four separate cavities; includes cattle, buffalo, camels, sheep and goats. |
| **scientific uncertainty** | Refers to the fact that our understanding of **global climate change** (e.g., the rate at which global temperatures will change and how other climate variables will change) is far from solid; that many unknowns remain. |
| **shortwave radiation** | Solar radiation in the visible, ultra-violet portion of the energy spectrum entering the top of the **atmosphere**, varying according to time of day, season of the year, and latitude; influx of shortwave radiation is balanced by **longwave** energy that is reflected and radiated back into space. |
| **stratospheric ozone** | Naturally occurring gas ($O_3$) that is concentrated in the stratosphere (higher atmosphere), the so-called **ozone layer**. |
| **sulfur dioxide** | A naturally occurring gas ($SO_2$), also emitted in the process of fossil fuel- or biomass burning. $SO_2$ is one of the emissions that has a cooling rather than a warming effect. |
| **survival emissions** | Emissions resulting from consumption that is essential to people's survival (as opposed to those used as luxury items) (Compare **luxury emissions**). |
| **technology transfer** | Transfer of latest technology from industrialized to developing countries. In the case of energy-related technology, the purpose of transfer is to increase energy use without increasing greenhouse gas emissions. |
| **tropospheric ozone** | Ozone ($O_3$) that occurs in the lower atmosphere and is considered a health hazard (especially for lungs); it is the main ingredient of (summer) smog. |
| **upland dry rice farming** | Rice cultivation in upland areas, which does not involve flooding and is not a significant source of methane. (Compare **wetland paddy rice farming**.) |
| **wetland paddy rice farming** | Rice cultivation in fields that are flooded for much of the growing season with natural flood- or tide-waters or through irrigation, producing significant methane emissions. (Compare **upland dry rice farming**.) |

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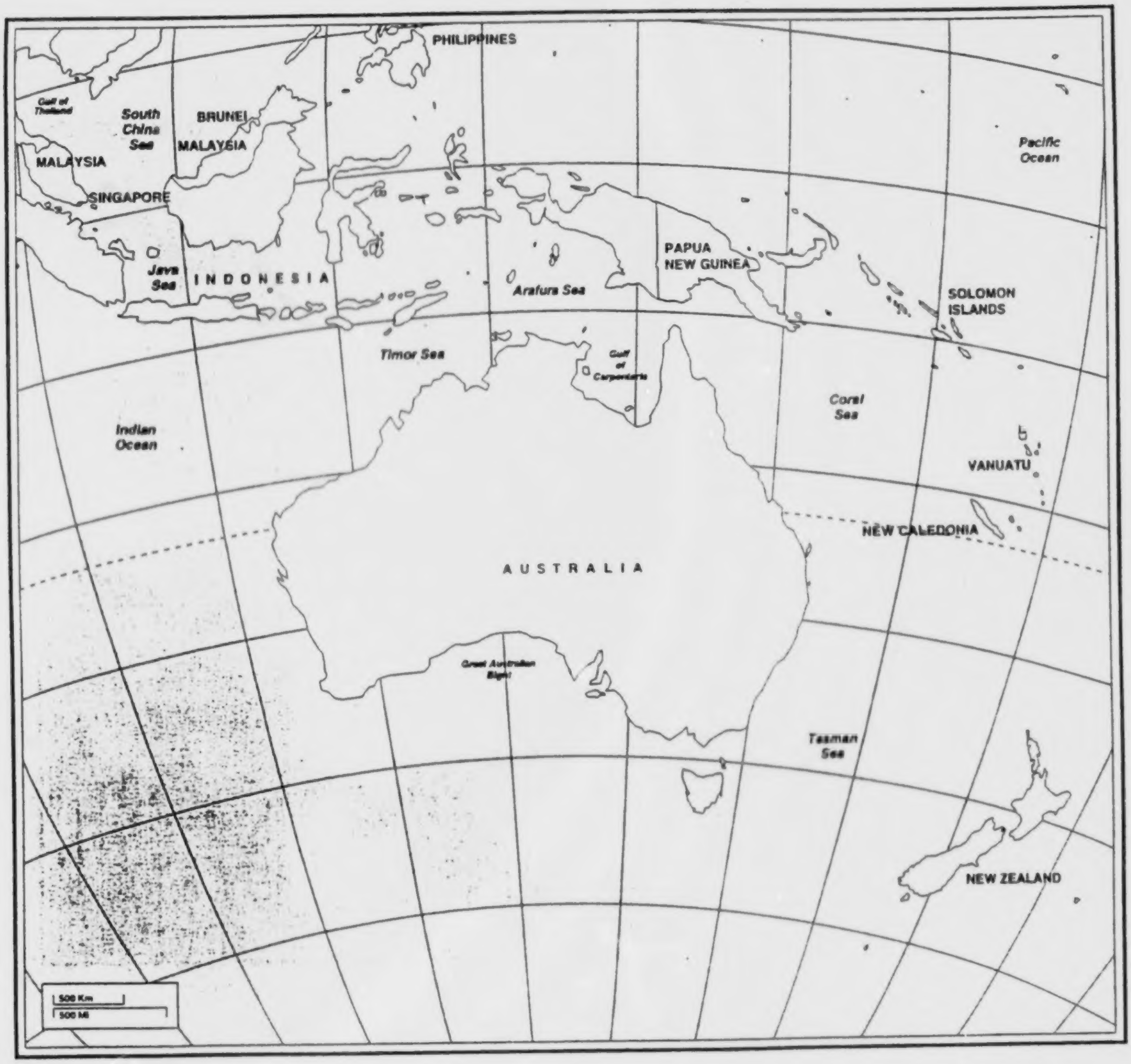
# Supporting Materials

The materials included in this section are meant to support the introduction and the carrying out of materials covered in this module, especially its activities. They may also be used as enhancements or extensions. Each item of *Supporting Material* is numbered according to the section or activity in which it may be used. For example, *Supporting Material 1.1* accompanies *Activity 1.1*.

# Regional Outline Maps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Gulf of Thailand
South China Sea
BRUNEI
MALAYSIA
MALAYSIA
SINGAPORE
Java Sea
INDONESIA
Pacific Ocean
PAPUA NEW GUINEA
Arafura Sea
SOLOMON ISLANDS
Timor Sea
Gulf of Carpentaria
Coral Sea
Indian Ocean
VANUATU
NEW CALEDONIA
AUSTRALIA
Great Australian Bight
Tasman Sea
NEW ZEALAND
500 Km
500 Mi

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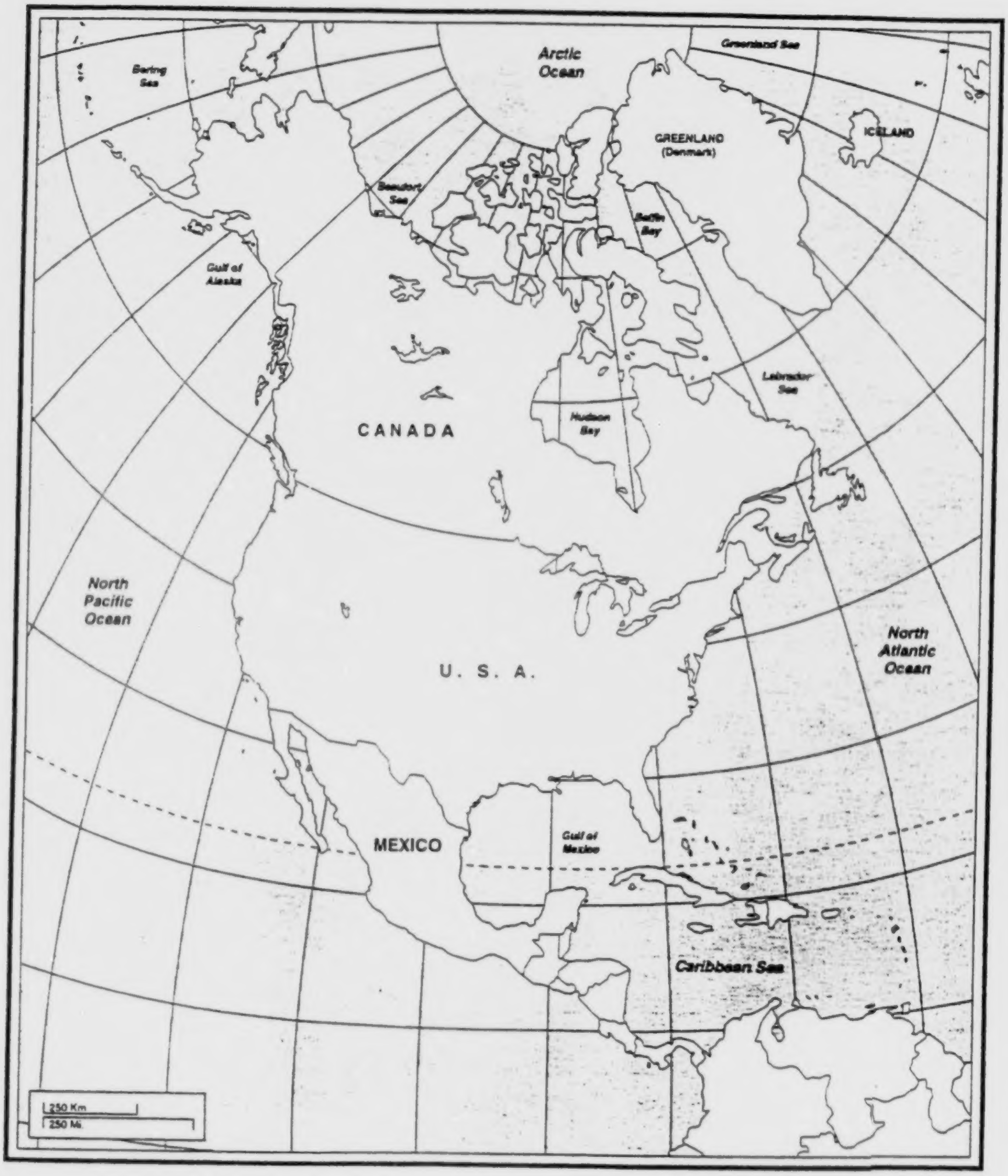
Bering Sea
Arctic Ocean
Greenland Sea
GREENLAND (Denmark)
ICELAND
Beaufort Sea
Baffin Bay
Gulf of Alaska
Labrador Sea
Hudson Bay
CANADA
North Pacific Ocean
U. S. A.
North Atlantic Ocean
MEXICO
Gulf of Mexico
Caribbean Sea
250 Km
250 Mi

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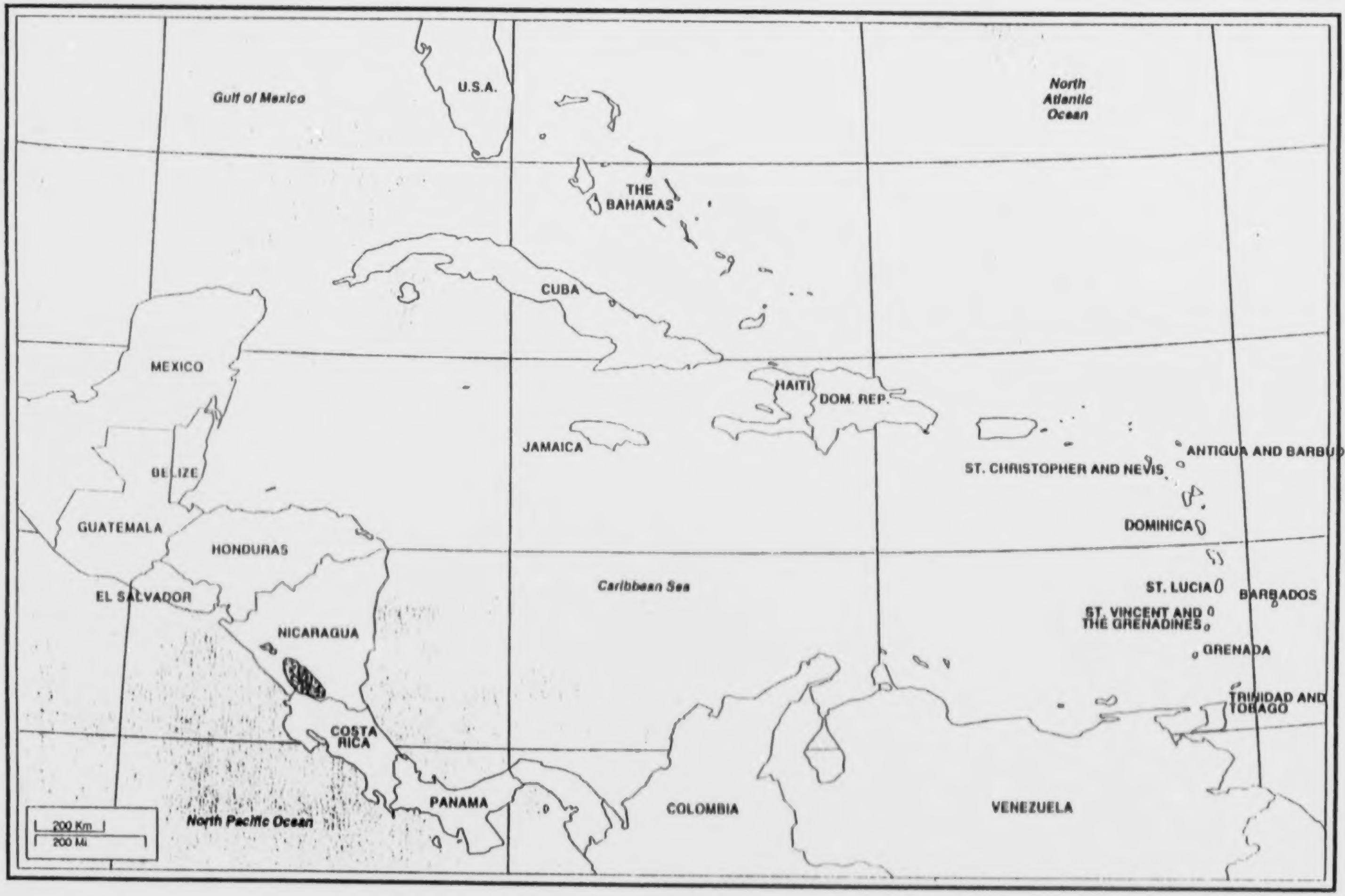
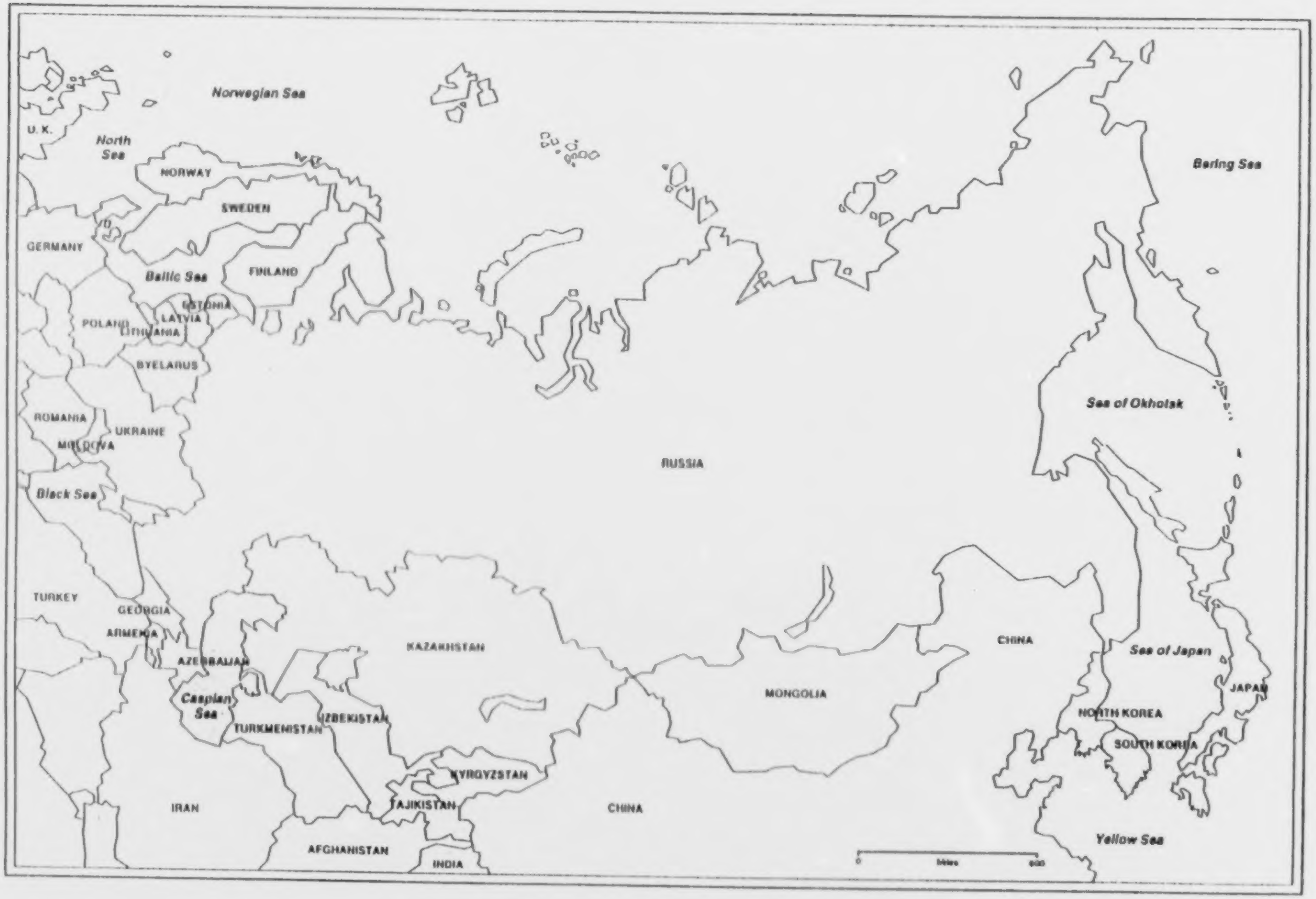

Gulf of Mexico
U.S.A.
North Atlantic Ocean
THE BAHAMAS
CUBA
MEXICO
HAITI
DOM. REP.
JAMAICA
ANTIGUA AND BARBUDA
ST. CHRISTOPHER AND NEVIS
BELIZE
GUATEMALA
DOMINICA
HONDURAS
Caribbean Sea
ST. LUCIA
BARBADOS
EL SALVADOR
ST. VINCENT AND THE GRENADINES
NICARAGUA
GRENADA
TRINIDAD AND TOBAGO
COSTA RICA
PANAMA
COLOMBIA
VENEZUELA
North Pacific Ocean
200 Km
200 Mi

Supporting Material 3.3d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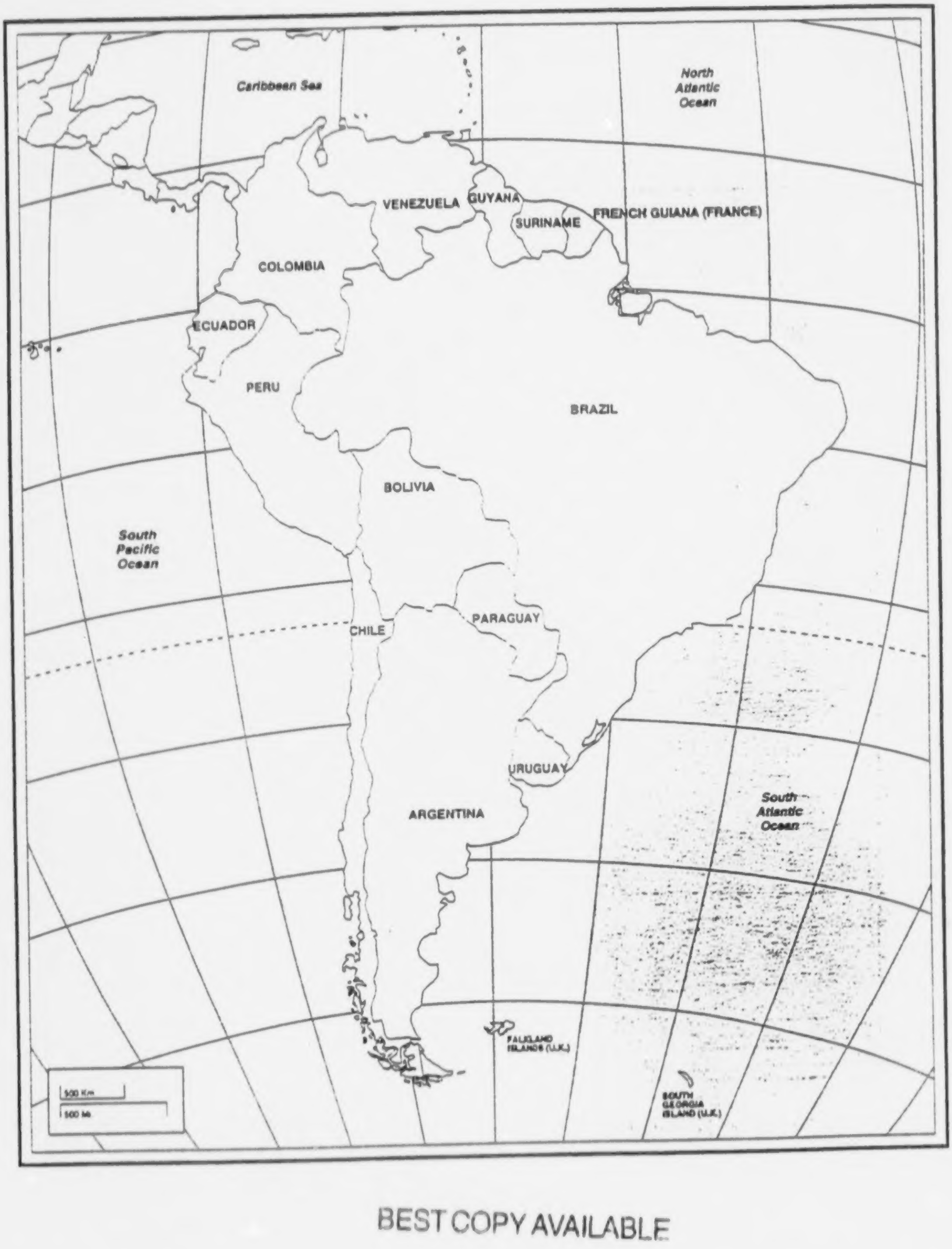
U.K.
North Sea
NORWAY
SWEDEN
GERMANY
Baltic Sea
FINLAND
ESTONIA
LATVIA
POLAND
LITHUANIA
BYELARUS
ROMANIA
UKRAINE
MOLDOVA
Black Sea
TURKEY
GEORGIA
ARMENIA
AZERBAIJAN
Caspian Sea
TURKMENISTAN
UZBEKISTAN
KAZAKHSTAN
KYRGYZSTAN
TAJIKISTAN
IRAN
AFGHANISTAN
INDIA
CHINA
MONGOLIA
RUSSIA
CHINA
Bering Sea
Sea of Okhotsk
Sea of Japan
JAPAN
NORTH KOREA
SOUTH KOREA
Yellow Sea


Caribbean Sea
North Atlantic Ocean
VENEZUELA
GUYANA
SURINAME
FRENCH GUIANA (FRANCE)
COLOMBIA
ECUADOR
PERU
BRAZIL
BOLIVIA
South Pacific Ocean
PARAGUAY
CHILE
URUGUAY
ARGENTINA
South Atlantic Ocean
FALKLAND ISLANDS (U.K.)
SOUTH GEORGIA ISLAND (U.K.)
500 Km
500 Mi

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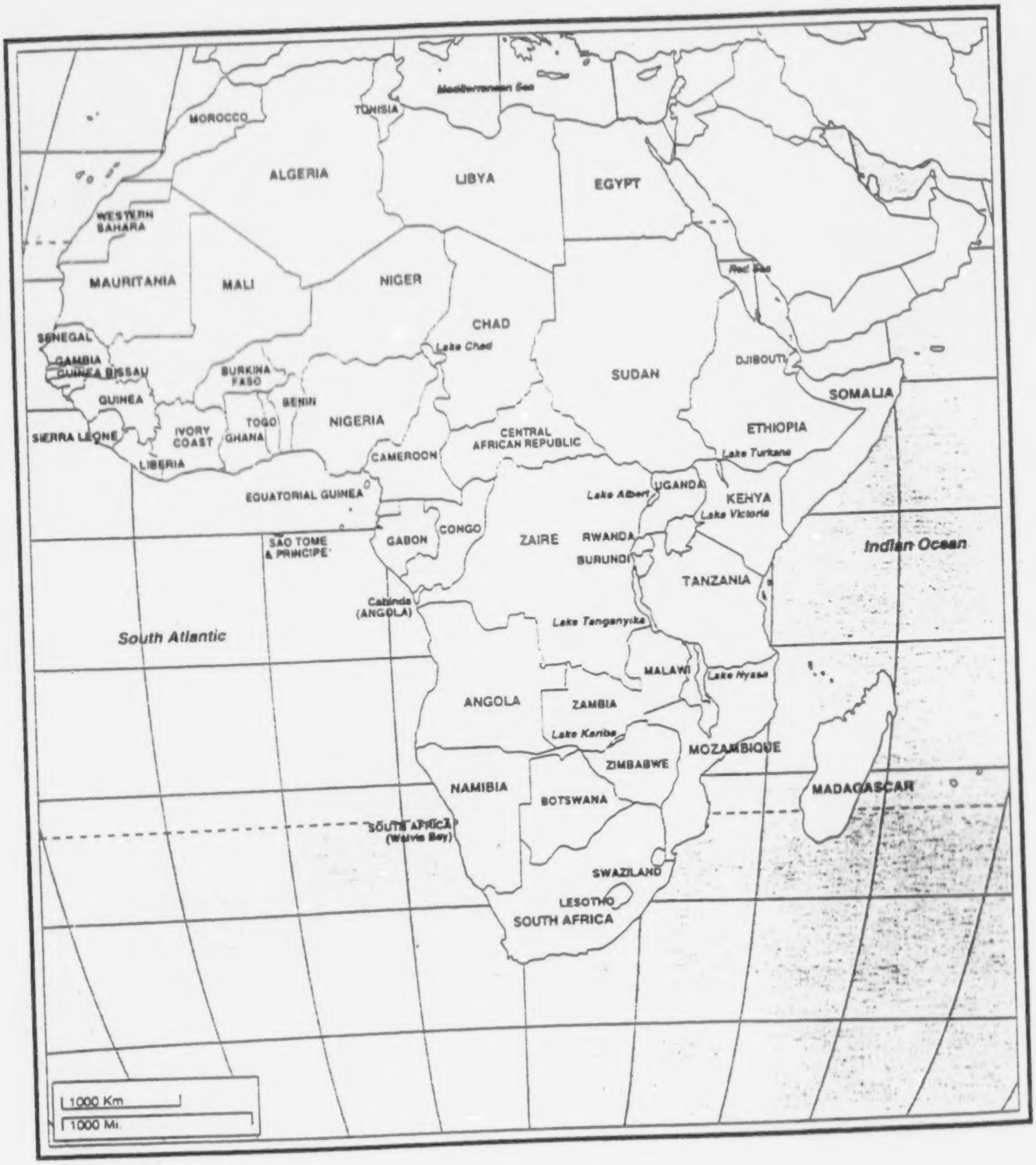
Supporting Material 3.3e


Mediterranean Sea
TUNISIA
MOROCCO
ALGERIA
LIBYA
EGYPT
WESTERN SAHARA
MAURITANIA
MALI
NIGER
Red Sea
CHAD
Lake Chad
SENEGAL
GAMBIA
GUINEA BISSAU
BURKINA FASO
DJIBOUTI
SUDAN
SOMALIA
GUINEA
BENIN
NIGERIA
TOGO
IVORY COAST
GHANA
SIERRA LEONE
LIBERIA
CAMEROON
CENTRAL AFRICAN REPUBLIC
ETHIOPIA
Lake Turkana
EQUATORIAL GUINEA
Lake Albert
UGANDA
KENYA
Lake Victoria
SAO TOME & PRINCIPE
GABON
CONGO
ZAIRE
RWANDA
BURUNDI
Indian Ocean
TANZANIA
Cabinda (ANGOLA)
South Atlantic
Lake Tanganyika
MALAWI
Lake Nyasa
ANGOLA
ZAMBIA
Lake Kariba
ZIMBABWE
MOZAMBIQUE
NAMIBIA
BOTSWANA
MADAGASCAR
SOUTH AFRICA (Walvis Bay)
SWAZILAND
LESOTHO
SOUTH AFRICA
1000 Km
1000 Mi.

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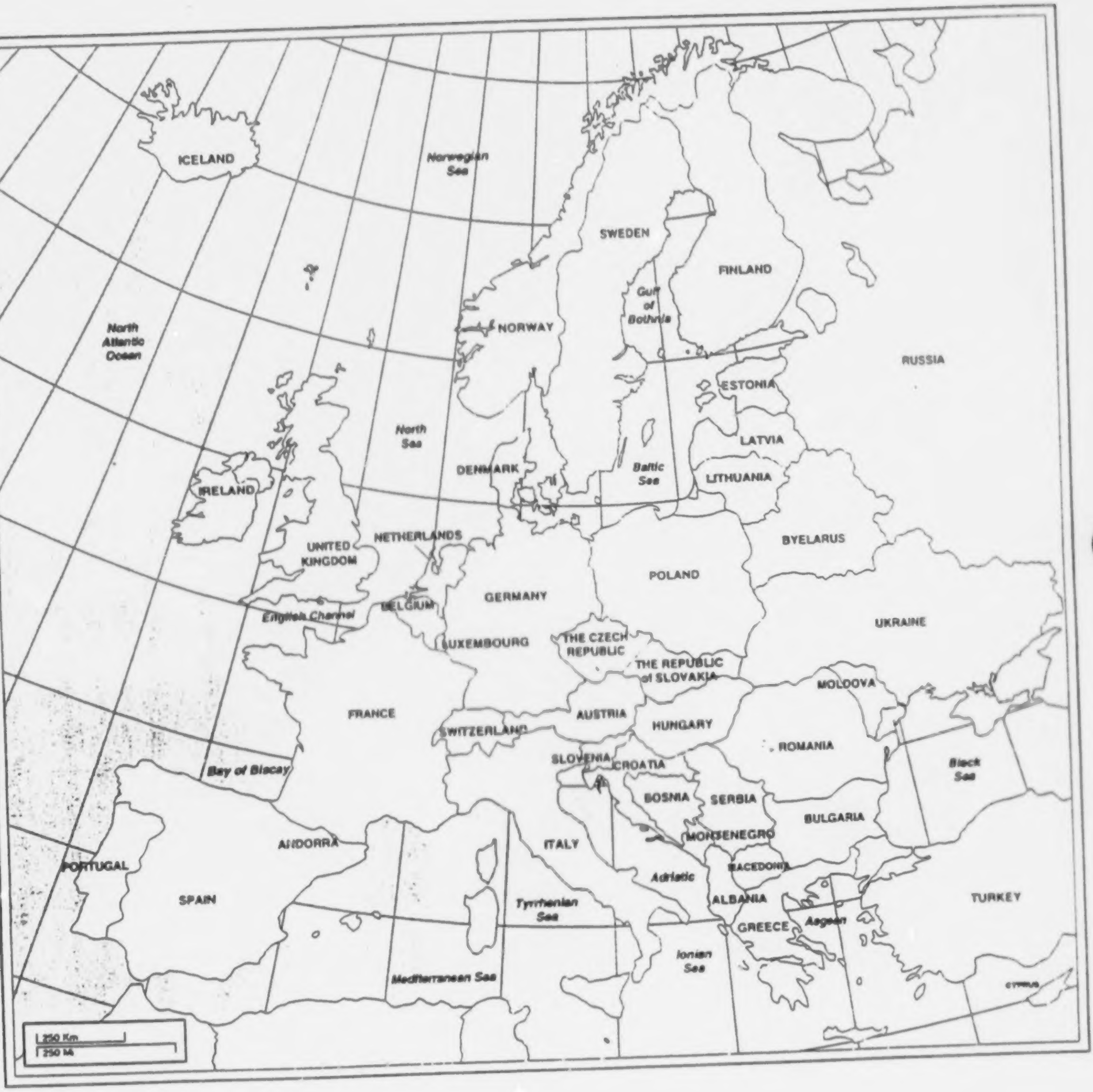
ICELAND
Norwegian Sea
SWEDEN
FINLAND
Gulf of Bothnia
NORWAY
North Atlantic Ocean
RUSSIA
ESTONIA
North Sea
LATVIA
DENMARK
Baltic Sea
LITHUANIA
IRELAND
UNITED KINGDOM
NETHERLANDS
BYELARUS
POLAND
GERMANY
BELGIUM
English Channel
UKRAINE
LUXEMBOURG
THE CZECH REPUBLIC
THE REPUBLIC of SLOVAKIA
MOLDOVA
FRANCE
AUSTRIA
SWITZERLAND
HUNGARY
ROMANIA
SLOVENIA
CROATIA
Bay of Biscay
Black Sea
BOSNIA
SERBIA
BULGARIA
MONTENEGRO
ANDORRA
ITALY
MACEDONIA
PORTUGAL
Adriatic
SPAIN
ALBANIA
TURKEY
Tyrrhenian Sea
GREECE
Aegean
Ionian Sea
Mediterranean Sea
CYPRUS
250 Km
250 Mi

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# Appendices

## Appendix A: On-line (Internet) Sources

CIESIN and its Socioeconomic Data and Applications Center (SEDAC) recently released the Policy Instruments Database (PIDB), an on-line tool for browsing and searching for text, summaries and status of treaties and other international agreements related to global environmental change. PIDB permits internet users with a World Wide Web browser or telnet access to query about environmental treaties and get answers within moments. The World Wide Web Uniform Resource Locator for the PIDB is http://sedac.ciesin.orb/pidb/pidb-home.html. For more information you can contact CIESIN by e-mail at pidb@ciesin.org or call CIESIN User Services at 517-797-2727.

Listed below are several useful climate change-related internet sources ("Climate servers"), and the IPCC homepage where you can access a list of IPCC reports which you may download or order if you want additional information on climate change.

*Framework Convention on Climate Change* -- http://www.iisd.ca/linkages/climate/climate.html

*Global Climate Change Information Programme* -- http://www.doc.mmu.ac.uk/aric/gccres.html

*Global Environmental Change Programme* -- http://www.susx.ac.uk/Units/gec/subject.html

*Global Environment Research Program* -- http://rpgopher.aist.go.jp:8000/nss/text/global.html

*Intergovernmental Panel on Climate Change* -- http://www.usgcrp.gov/ipcc/html/aboutipc.html

### Additional interesting sites to check out

*Greenpeace* -- http://www.greenpeace.org/!climate/index.html

*The Global Climate Coalition* -- http://www.worldcorp.com/dc-online/gcc/index.html

*Climate Action Network* -- http://www.woodwind.com/imaja/Change/environment/can/can.html

# Appendix B: Films to Accompany this Module

Below we suggest films that could be used with this module. For the first, a part of the *Race to Save the Planet* series, we also suggest an additional study guide for instructors that has been published for use with an environmental studies textbook. The films may be used to introduce the module, especially with Unit 1, but would work well with any unit to bring the issues to life.

To obtain the films, you may check in your local video store or else use interlibrary loan, your library's video archives, or the original publisher. Allow enough time to obtain the films if you plan to use interlibrary loan, or order the films.

***Race to save the planet*** - Series
S. Burlington, VT: The Annenberg/CPB Collection, 1990
10 videocassettes (ca. 58 min. each): sd., col. ; 1/2 in., VHS format.

no. 1. Environmental revolution --
no. 2. *Only one atmosphere* -- (see description below)
no. 3. Do we really want to live this way? --
no. 4. In the name of progress --
no. 5. Remnants of Eden --
no. 6. More for less --
no. 7. Save the earth, feed the world --
no. 8. Waste not, want not --
no. 9. It needs political decisions --
no. 10. Now or never.

Cinematography: Peter Hoving, Richard Lerner, Tom Hurwitz [et al...]; Music: Jeff Lass, Caleb Morgan; Animation & graphics: Jed Schwartz, Larry Giunta [et al...]; Host: Meryl Streep; Narrator: Roy Scheider.

Abstract: Shows ways that the physical environment of the Earth is being changed by man and suggests actions to preserve it.

Wolf, Edward C. 1995. *Race to save the planet: Study guide*. Belmont, Calif. : Wadsworth Publishing Co., 184 pp.: ill., maps; 28 cm.
"Part of a college-level telecourse... produced by WGBH-TV, Boston."
"Keyed to Living in the environment, eighth edition, and
Environmental science, fifth edition."
Includes bibliographical references.
ISBN: 0534250386

### *Only one atmosphere*

Santa Barbara, CA.: Intellimation [distributor], 1990
1 videocassette (ca. 60 min.) : sd., col. ; 1/2 in.
Race to save the planet series; no. 2
Annenberg CPB collection
Closed-captioned for the hearing impaired.
Originally shown on PBS.

Written, produced, and directed by Andrew Liebman; editor, Eric Neudel; Executive producer, John Angier. Host, Meryl Streep; Narrator, Roy Scheider.

Abstract: Explores the global commons of the atmosphere. Explains that the worldwide impact of global warming demands an international response that may be considered the largest environmental challenge society has ever faced. Series concept based on the Worldwatch Institute's State of the world reports.

Series accompanied by study guide.
ISBN: 1559463333

### *After the warming*

Chicago, Il.: Clearvue/eav, 1990
2 videocassettes (110 min.): sd., col.; VHS format, 1/2 in. + 1 teacher's guide (36 p.: ill.; 28 cm.)
Part 1. The fatal flower -- Part 2. Secret of the deep.

Director of photography, Noel Jones; Music, Richard Elfyn Jones; Graphic artists, Darren Agnew, Somon Brewster, Paul Farrell. Presenter, James Burke.

Abstract: Social journalist James Burke presents several possible scenarios caused by the greenhouse effect from the 1990s to 2050.

# Appendix C: Understanding Climate Change: A Beginner's Guide to the UN Framework Convention

Published by the UNEP/WMO Information Unit on Climate Change (IUCC). Printed in December 1994. Permission is granted to reproduce the contents giving appropriate credit. For more information, contact IUCC, United Nations Environment Programme (UNEP), Geneva Executive Center, Box 356, 1219 Châtelaine, Switzerland.

## Introduction

A giant asteroid could hit the Earth! Something else could happen! The global temperature could rise! Wake up!

The 1990s have been a time of international soul- searching about the environment. What are we doing to our planet? More and more, we are realizing that the Industrial Revolution has changed forever the relationship between humanity and nature. There is real concern that by the middle or the end of the next century human activities will have changed the basic conditions that have allowed life to thrive on Earth.

The 1992 United Nations Framework Convention on Climate Change is one of a series of recent agreements through which countries around the world are banding together to meet this challenge. Other treaties deal with such matters as pollution of the oceans, expanding deserts, damage to the ozone layer, and the rapid extinction of plant and animal species. The Climate Change Convention focuses on something particularly disturbing: we are changing the way energy from the sun interacts with and escapes from our planet's atmosphere. By doing that, we risk altering the global climate. Among the expected consequences are an increase in the average temperature of the Earth's surface and shifts in world-wide weather patterns. Other -- unforeseen -- effects cannot be ruled out.

## We have a few problems to face up to

*Problem No. 1 (the big problem): Scientists see a real risk that the climate will change rapidly and dramatically over the coming decades and centuries. Can we handle it?*

A giant asteroid did hit the Earth -- about 65 million years ago. Splat. Scientists speculate that the collision threw so much dust into the atmosphere that the world was dark for three years. Sunlight was greatly reduced, so many plants could not grow, temperatures fell, the food chain collapsed, and many species, including the largest ever to walk the Earth, died off.

That, at least, is the prevailing theory of why the dinosaurs became extinct. Even those who weren't actually hit by the asteroid paid the ultimate price. The catastrophe that befell the dinosaurs is only one illustration, if dramatic, of how changes in climate can make or break a species.

According to another theory, human beings evolved when a drying trend some 10 million years ago was followed around three million years ago by a sharp drop in world temperature. The ape-like higher primates in the Great Rift Valley of Africa were used to sheltering in trees, but, under this long-term climate shift, the trees were replaced with grassland. The 'apes' found themselves on an empty plain much colder and drier than what they were used to, and extremely vulnerable to predators.

Extinction was a real possibility, and the primates appear to have responded with two evolutionary jumps -- first to creatures who could walk upright over long distances, with hands free for carrying children and food; and then to creatures with much larger brains, who used tools and were omnivorous (could eat both plants and meat). This second, large-brained creature is generally considered to be the first human.

Shifts in climate have shaped human destiny ever since, and people have largely responded by adapting, migrating, and growing smarter. During a later series of ice ages, sea levels dropped and humans moved across land bridges from Asia to the Americas and the Pacific islands. Many subsequent migrations, many innovations, many catastrophes have followed. Some can be traced to smaller climatic fluctuations, such as a few decades or centuries of slightly higher or lower temperatures, or extended droughts. Best known is the Little Ice Age that struck Europe in the early Middle Ages, bringing famines, uprisings, and the withdrawal of northern colonies in Iceland and Greenland. People have suffered under the whims of climate for millennia, responding with their wits, unable to influence these large events.

Until now. Ironically, we humans have been so remarkably successful as a species that we may have backed ourselves into a corner. Our numbers have grown to the point where we have less room for large-scale migration should a major climate shift call for it. And the products of our large brains -- our industries, transport, and other activities -- have led to something unheard of in the past. Previously the global climate changed human beings. Now human beings seem to be changing the global climate. The results are uncertain, but if current predictions prove correct, the climatic changes over the coming century will be larger than any since the dawn of human civilization.

The principal change to date is in the Earth's atmosphere. The giant asteroid that felled the dinosaurs threw large clouds of dust into the air, but we are causing something just as profound if more subtle. We have changed, and are continuing to change, the balance of gases that form the atmosphere. This is especially true of such key "greenhouse gases" as carbon dioxide ($CO_2$), methane (CH4), and nitrous oxide ($N_2O$). (Water vapor is the most important greenhouse gas, but human activities do not affect it directly.) These naturally occurring gases make up less than one tenth of one per cent of the total atmosphere, which consists mostly of oxygen (21 per cent) and nitrogen (78 per cent). But greenhouse gases are vital because they act like a blanket around the Earth. Without this natural blanket the Earth's surface would be some 30 °C colder than it is today.

The problem is that human activity is making the blanket "thicker." For example, when we burn coal, oil, and natural gas we spew huge amounts of carbon dioxide into the air. When we destroy forests the carbon stored in the trees escapes to the atmosphere. Other basic activities, such as raising cattle and planting rice, emit methane, nitrous oxide, and other greenhouse gases. If emissions continue to grow at current rates, it is almost certain that atmospheric levels of carbon dioxide will double from pre-industrial levels during the 21st century. If no steps are taken to slow greenhouse gas emissions, it is quite possible that levels will triple by the year 2100.

The most direct result, says the scientific consensus, is likely to be a "global warming" of 1.5 to 4.5 °C over the next 100 years. That is in addition to an apparent temperature increase of half a degree Centigrade since the pre-industrial period before 1850, at least some of which may be due to past greenhouse gas emissions.

Just how this would affect us is hard to predict because the global climate is a very complicated system. If one key aspect -- such as the average global temperature -- is altered, the ramifications ripple outward. Uncertain effects pile onto uncertain effects. For example, wind and rainfall patterns that have prevailed for hundreds or thousands of years, and on which millions of people depend, may change. Sea-levels may rise and threaten islands and low-lying coastal areas. In a world that is increasingly crowded and under stress -- a world that has enough problems already -- these extra pressures could lead directly to more famines and other catastrophes.

While scientists are scrambling to understand more clearly the effects of our greenhouse gas emissions, countries around the globe recently joined together to confront the problem.

## How the Convention responds

It recognizes that there is a problem. That's a significant step. It is not easy for the nations of the world to agree on a common course of action, especially one that tackles a problem whose consequences are uncertain and which will be more important for our grandchildren than for the present generation. Still, the Convention was negotiated and signed by 165 states in a little over two years, and over 100 have already ratified and so are legally bound by it. The treaty took effect on 21 March 1994.

The Convention also sets an "ultimate objective" of stabilizing "greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic (human-induced) interference with the climate system." The objective does not specify what these concentrations should be, only that they be at a level that is not dangerous. This acknowledges that there is currently no scientific certainty about what a dangerous level would be. Scientists believe it will take about another decade (and the next generation of supercomputers) before today's uncertainties (or many of them) are significantly reduced. The Convention's objective thus remains meaningful no matter how the science evolves.

The Convention furthermore directs that "such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner." This highlights the main concerns about food production -- probably the most climate-sensitive human activity -- and economic development. It also suggests (as most climatologists believe) that some change is inevitable and that adaptive as well as preventive measures are called for.

Again, this leaves room for interpretation in the light of scientific findings and the trade-offs and risks that the global community is willing to accept.

*Problem No. 2: If the consequences of a problem are uncertain, do you ignore the problem or do you do something about it anyway?*

Climate change is a threat to mankind. But no one is certain about its future effects or their severity. Responding to the threat is expected to be expensive, complicated, and difficult. There is even some disagreement over whether any problem exists at all: while many people worry that the effects will be extremely serious, others argue that scientists cannot prove that what they suspect will happen will actually happen. In addition, it is not clear who (in the various regions of the world) will suffer most. Yet if the nations of the world wait until the consequences and victims are clear, it will probably be too late to act. What should we do?

The truth is that in most scientific circles the issue is no longer whether or not climate change is a potentially serious problem. Rather, it is how the problem will develop, what its effects will be, and how these effects can best be detected. Computer models of something as complicated as the planet's climate system are not far enough advanced yet to give clear and unambiguous answers. Nevertheless, while the when, where, and how remain uncertain, the big picture painted by these climate models cries out for attention. For example:

Regional rain patterns may change. At the global level, the evapo-transpiration cycle is expected to speed up. This means that it would rain more, but the rain would evaporate faster, leaving soils drier during critical parts of the growing season. New or worsening droughts, especially in poorer countries, could reduce supplies of clean, fresh water to the point where there are major threats to public health. Because they still lack confidence in regional scenarios, scientists are uncertain about which areas of the world risk becoming wetter and which drier. But with global water resources already under severe strain from rapid population growth and expanding economic activity, the danger is clear.

Climate and agricultural zones may shift toward the poles. In the mid-latitude regions the shift is expected to be 200 to 300 kilometres for every degree Celsius of warming. Increased summer dryness may reduce mid- latitude crop yields by 10 to 30 per cent, and it is possible that today's leading grain-producing areas (such as the Great Plains of the United States) would experience more frequent droughts and heat waves. The poleward edges of the mid-latitude agricultural zones -- northern Canada, Scandinavia, Russia, and Japan in the northern hemisphere, and southern Chile and Argentina in the southern hemisphere -- might benefit from higher temperatures. However, rugged terrain and poor soil would prevent these countries from compensating for reduced yields in today's more productive areas.

Melting glaciers and the thermal expansion of sea water may raise sea levels, threatening low-lying coastal areas and small islands. The global mean sea level has already risen by around 15 centimetres during the past century, and global warming is expected to cause a further rise of about 18 cm by the year 2030. If the current trend in greenhouse gas emissions continues, the rise could amount to 65 cm above current levels by the year 2100. The most vulnerable land would be the unprotected, densely populated coastal regions of some of the world's poorest countries. Bangladesh, whose coast is already prone to devastating floods, would be a likely victim, as would many small island states such as the Maldives.

These scenarios are alarming enough to raise concern, but too uncertain to enable governments to make many specific decisions about what to do. The picture is fuzzy. Some governments, beleaguered by other problems and responsibilities and bills to pay, understandably are tempted to do nothing at all. Maybe the threat will go away. Or someone else will deal with it. Maybe another giant asteroid will hit the Earth. Who knows?

## How the Convention responds

It establishes a framework and a process for agreeing to specific actions -- later. The diplomats who wrote the Framework Convention on Climate Change saw it as a launching pad for potential further action in the future. They recognized that it would not be possible in the year 1992 for the world's governments to agree on a detailed blueprint for tackling climate change. But by establishing a framework of general principles and institutions, and by setting up a process through which governments can meet regularly, they got things started.

A key benefit of this approach is that it allows countries to begin discussing an issue even before they all fully agree that it is, in fact, a problem. Even skeptical countries feel it is worthwhile participating. (Or, to put it another way, they'd feel uneasy about being left out.) This creates legitimacy for the issue, and a sort of international peer pressure to take the subject seriously.

The Convention is designed to allow countries to weaken or strengthen the treaty in response to new scientific developments. For example, they can agree to take more specific actions (such as reducing emissions of greenhouse gases by a certain amount) by adopting "amendments" or "protocols" to the Convention.

The treaty promotes action in spite of uncertainty on the basis of a recent development in international law and diplomacy called the "precautionary principle." Under traditional international law, an activity generally has not been restricted or prohibited unless a direct causal link between the activity and a particular damage can be shown. But many environmental problems, such as damage to the ozone layer and pollution of the oceans, cannot be confronted if final proof of cause and effect is required. In response, the international community has gradually come to accept the precautionary principle, under which activities that threaten serious or irreversible damage can be restricted or even prohibited before there is absolute scientific certainty about their effects.

The Convention takes preliminary steps that clearly make sense for the time being. Countries ratifying the Convention -- called "Parties to the Convention" in diplomatic jargon -- agree to take climate change into account in such matters as agriculture, energy, natural resources, and activities involving sea-coasts. They agree to develop national programs to slow climate change. The Convention encourages them to share technology and to cooperate in other ways to reduce greenhouse gas emissions, especially from energy, transport, industry, agriculture, forestry, and waste management, which together produce nearly all greenhouse gas emissions attributable to human activity.

The Convention encourages scientific research on climate change. It calls for data gathering, research, and climate observation, and it creates a "subsidiary body" for "scientific and technological advice" to help governments decide what to do next. Each country that is a Party to the Convention must also develop a greenhouse gas "inventory" listing its national sources (such as factories and transport) and "sinks" (forests and other natural ecosystems that absorb greenhouse gases from the atmosphere). These inventories will have to be updated regularly and made public. The information they provide on which activities emit how much of each gas will be essential for monitoring changes in emissions and determining the effects of measures taken to control emissions.

*Problem No. 3: It's not fair.*

If a giant asteroid hits the Earth, that's nobody's fault. The same cannot be said for global warming.

There is a fundamental unfairness to the climate change problem that chafes at the already uneasy relations between the rich and poor nations of the world. Countries with high standards of living are mostly (if unwittingly) responsible for the rise in greenhouse gases. These early industrializers -- Europe, North America, Japan, and a few others -- created their wealth in part by pumping into the atmosphere vast amounts of greenhouse gases long before the likely consequences were understood. Developing countries now fear being told that they should curtail their own fledgling industrial activities -- that the atmosphere's safety margin is all used up. Because energy-related emissions are the leading cause of climate change, there will be growing pressure on all countries to reduce the amounts of coal and oil they use. There also will be pressure (and incentives) to adopt advanced technologies so that less damage is inflicted in the future. Buying such technologies can be costly.

Countries in the early stages of industrialization -- countries struggling hard to give their citizens better lives -- don't want these additional burdens. Economic development is difficult enough already. If they agreed to cut back on burning the fossil fuels that are the cheapest, most convenient, and most useful for industry, how could they make any progress?

There are other injustices to the climate change problem. The countries to suffer the most if the predicted consequences come about -- if agricultural zones shift or sea levels rise or rainfall patterns change -- will probably be in the developing world. These nations simply do not have the scientific or economic resources, or the social safety nets, to cope with disruptions in climate.

Also, in many of these countries rapid population growth has pushed many millions of people onto marginal land -- the sort of land that can change most drastically due to variations in climate.

## How the Convention responds

It puts the lion's share of the responsibility for battling climate change -- and the lion's share of the bill -- on the rich countries. The Convention notes that the largest share of historical and current emissions originates in developed countries. Its first basic principle is that these countries should take the lead in combating climate change and its adverse impacts. Specific commitments in the treaty relating to financial and technological transfers apply only to the 24 developed countries belonging to the Organization for Economic Cooperation and Development (OECD -- excepting Mexico, which joined the OECD in 1994). They agree to support climate change activities in developing countries by providing financial support above and beyond any financial assistance they already provide to these countries.

Specific commitments concerning efforts to limit greenhouse gas emissions and enhance natural sinks apply to the OECD countries as well as to 12 "economies in transition" (Central and Eastern Europe and the former Soviet Union). Although negotiations left the treaty language less than clear, it is generally accepted that the OECD and transition countries should at a minimum seek to return by the year 2000 to the greenhouse gas emission levels they had in 1990.

The Convention recognizes that poorer nations have a right to economic development. It notes that the share of global emissions of greenhouse gases originating in developing countries will grow as these countries expand their industries to improve social and economic conditions for their citizens.

It acknowledges the vulnerability of poorer countries to the effects of climate change. One of the Convention's basic principles is that the specific needs and circumstances of developing countries should be given "full consideration" in any actions taken. This applies in particular to those whose fragile ecosystems are highly vulnerable to the impacts of climate change. The Convention also recognizes that states which depend on income from coal and oil would face difficulties if energy demand changes.

*Problem No. 4: If the whole world starts consuming more and living the good life, can the planet stand the strain?*

As the human population continues to grow, the demands human beings place on the environment increase. The demands are becoming all the greater because these rapidly increasing numbers of people also want to live better lives. More and better food, more and cleaner water, more electricity, refrigerators, automobiles, houses and apartments, land on which to put houses and apartments. Already there are severe problems supplying enough fresh water to the world's billions. Burgeoning populations are draining the water from rivers and lakes, and vast underground aquifers are steadily being depleted. What will people do when these natural "tanks" are empty? There are also problems growing and distributing enough food -- widespread hunger in many parts of the world attests to that. There are other danger signals. The global fish harvest has declined sharply; as large as the oceans are, the most valuable species have been effectively fished out.

Global warming is a particularly ominous example of humanity's insatiable appetite for natural resources. During the last century we have dug up and burned massive stores of coal, oil, and natural gas that took millions of years to accumulate. Our ability to burn up fossil fuels at a rate that is much, much faster than the rate at which they were created has upset the natural balance of the carbon cycle. The threat of climate change arises because one of the only ways the atmosphere -- also a natural resource -- can respond to the vast quantities of carbon being liberated from beneath the Earth's surface is to warm up.

Meanwhile, human expectations are not tapering off. They are increasing. The countries of the industrialized "North" have 20 per cent of the world's people but use about 80 percent of the world's resources. By global standards, they live extremely well. It's nice living the good life, but if everyone consumed as much as the North Americans and Western Europeans consume -- and billions of people aspire to do just that -- there probably would not be enough clean water and other vital natural resources to go around. How will we meet these growing expectations when the world is already under so much stress?

## How the Convention responds

It supports the concept of "sustainable development." Somehow, humankind must learn how to alleviate poverty for huge and growing numbers of people without destroying the natural environment on which all human life depends. Somehow a way has to be found to develop economically in a fashion that is sustainable over a long period of time. The buzzword for this challenge among environmentalists and international bureaucrats is "sustainable development." The trick will be to find methods for living well while using critical natural resources at a rate no faster than that at which they are replaced. Unfortunately, the international community is a lot farther along in defining the problems posed by sustainable development than it is in figuring out how to solve them.

The Convention calls for developing and sharing environmentally sound technologies and know-how. Technology will clearly play a major role in dealing with climate change. If we can find practical ways to use cleaner sources of energy, such as solar power, we can reduce the consumption of coal and oil. Technology can make industrial processes more efficient, water purification more viable, and agriculture more productive for the same amount of resources invested. Such technology must be made widely available -- it must somehow be shared by richer and more scientifically advanced countries with poorer countries that have great need of it.

The Convention emphasizes the need to educate people about climate change. Today's children and future generations must learn to look at the world in a different way than it has been looked at by most people during the 20th century. This is both an old and a new idea. Many (but not all!) pre-industrial cultures lived in balance with nature. Now scientific research is telling us to do much the same thing. Economic development is no longer a case of "bigger is better" -- bigger cars, bigger houses, bigger harvests of fish, bigger doses of oil and coal. We must no longer think of human progress as a matter of imposing ourselves on the natural environment. The world -- the climate and all living things -- is a closed system; what we do has consequences that eventually come back to affect us. Tomorrow's children -- and today's adults, for that matter -- will have to learn to think about the effects of their actions on the climate. When they make decisions as members of governments and businesses, and as they go about their private lives, they will have to take the climate into account.

In other words, human behavior will have to change -- probably the sooner the better. But such things are difficult to prescribe and predict. There is, for example, the matter of what sacrifices might have to be made by everyone for the good of the global climate. That leads to...

*Problem No. 5: Who has the energy, time, or money left to deal with climate change, when we have so many other problems?*

A valid point.

### How the Convention responds

It starts slowly. It doesn't make too many demands (or requests) for the time being. But stay tuned. The Framework Convention on Climate Change is a general treaty with just a few specific requirements. More and bigger requirements may come later, in the form of amendments and protocols. This will happen as scientific understanding of climate change becomes clearer and as the countries of the world, already suffering from a case of "disaster fatigue," adjust to the idea that they have yet another crisis to face and pay for. War, famine, AIDS, the ozone "hole," acid rain, the loss of ecosystems and species ... Thinking about these problems, people could be forgiven for wondering if they should throw in the towel.

We can't give up, of course. And while the Convention cannot claim to have the issue all sorted out, it does make a start. Things are beginning to happen. Developed countries are making national plans with the aim of returning their greenhouse gas emissions to 1990 levels by the year 2000 -- thereby reversing the historical trend of ever-increasing emissions. Countries that have ratified the treaty are beginning to gather data on their emissions and on the present climate. More and more, people and governments are talking and thinking about climate change.

## How policy-makers are responding to global climate change (UNEP)

The first time climate change was recognized as a serious problem by a major intergovernmental meeting was in 1979. The First World Climate Conference, held in February of that year, was an important scientific event. It issued a declaration calling on the world's governments "to foresee and prevent potential man-made changes in climate that might be adverse to the well-being of humanity."

A large number of international conferences on climate change have been convened since then. Attended by government policy-makers, scientists, and environmental groups, they have addressed both scientific and policy issues. Important meetings have been held in Toronto, the Hague, Noordwijk, Bergen, and elsewhere. The Second World Climate Conference, held in 1990 in Geneva, was a particularly crucial step toward a binding global convention on climate change. Some of these meetings have taken place under the auspices of the United Nations and its specialized agencies. Others have been held within regional and global fora such as the European Community, the Commonwealth, and the South Pacific Forum, or have been convened by individual governments. A number of meetings have been dedicated to the particular concerns of small island states and of developing countries.

The 1992 UN Framework Convention on Climate Change is the first binding international legal instrument to address the issue specifically. Adopted after 15 months of intensive negotiations within the Intergovernmental Negotiating Committee for a Framework Convention on Climate Change (INC/FCCC - see fact sheet 209), it was opened for signature in Rio de Janeiro at the June 1992 UN Conference on Environment and Development (UNCED). The INC negotiators drew on the First Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), a body established jointly by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO). They were also influenced by the Ministerial Declaration issued by the Second World Climate Conference and by policy statements adopted by numerous other climate conferences. The Convention incorporates a number of newly emerging legal principles that had been developed or affirmed by various climate conferences.

The Convention will provide a general framework for addressing the climate change issue. The Convention was signed by 154 states and the European Community during UNCED. Other states have signed since then, and some national legislatives have ratified. States must now strive to ensure that the Convention enters into force as soon as possible. At the same time, government experts must decide whether to adopt additional measures in future annexes and protocols to the Convention. These protocols may set out more specific commitments, such as timetables for reducing greenhouse gas emissions.

Even before the Convention was adopted, some countries had already taken unilateral action at the national level. Most OECD member states have set national targets for stabilizing or reducing their emissions of greenhouse gases. In 1990, the Council of the European Communities (EC) adopted a policy that provides for stabilizing the emissions of carbon dioxide -- the most significant greenhouse gas -- at 1990 levels by the year 2000. A strategy to limit carbon dioxide emissions and to improve energy efficiency is currently being elaborated by the EC Commission.

In addition, two other international environmental treaties address climate change indirectly. The amended 1987 Montreal Protocol on Substances That Deplete the Ozone Layer legally obliges its parties to phase out chlorofluorocarbons (CFCs) by the year 1996. Although inspired by concern over the destruction of the ozone layer, this protocol is significant also for climate change since CFCs are greenhouse gases. Similarly, the 1979 Geneva Convention on Long-Range Transboundary Air Pollution and its protocols regulate the emission of noxious gases, some of which are precursors of greenhouse gases. These treaties, however, do not address the complex set of inter-related climate issues.

# Appendix D: Selected Readings

The following appendix contains a limited number of the suggested readings for this module. These are the only readings for which the AAG was able to obtain copyright permission. They may be copied and distributed to students currently enrolled in any course in which this module is being used. Instructors are advised to put these and the remaining suggested readings (which they have to find through the resources available at their institutions -- journal and book holdings and interlibrary loan) on reserve so that students can have access to them.

This appendix contains the following readings:

Global Climate Coalition. 1996a. *Index of Climate Resources*. http://www.worldcorp.com/dc-online/gcc/index.html

Global Climate Coalition. 1996b. *Trends in global greenhouse gas emissions.* http://www.worldcorp.com/dc-online/gcc/trends.html

Greenpeace International. 1996. *Greenpeace International Climate Crisis Homepage*. http://www.greenpeace.org/~climate/index.html

Hammond, Allen L., Eric Rodenburg, and William R. Moomaw. 1991. Calculating national accountability for climate change. *Environment* 33,1: 11-15, 33-35. Includes Commentary in *Environment* 33, 1: 179-185.

Intergovernmental Panel on Climate Change (IPCC). 1990. *Scientific assessment of climate change*. Geneva: UNEP/WMO.

UNEP/IUCC (Information Unit on Climate Change). 1996a. *Energy and greenhouse gas emissions*. Fact Sheet # 25. http://www.unep.ch/iucc/fs025.html

UNEP/IUCC.1996b. *The case for reducing greenhouse gas emissions despite scientific uncertainty*. Fact Sheet # 233. http://www.unep.ch/iucc/fs025.html

UNEP/IUCC.1996c. *Summary for Policymakers: The Science of Climate Change, IPCC Working Group I (1995)*. http://www.unep.ch/ipcc/sumwg1.html

# GLOBAL CLIMATE COALITION

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# Index of Climate Resources

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Welcome to the Global Climate Coalition's Index of Climate Resources. This web site has been created to begin cataloging the available climate change resources on the internet, including web pages, gophers, newsgroups, FTP a ddressees and Telnet information. The Index has been broken down into categories of Science, Economics, Policy and other established Indexes of climate change information. We have also provided an index of GCC documents, reports and background informati on, detailing business and industry's views on climate issues.

The Index of Climate Resources will continue to expand as new sites are discovered. If you know of a site not currently listed, please email us with the appropriate information. Your consideration and cooperation will help this site thrive.

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Science Policy Economic Indexes

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## GCC Documents Directory

You can view and download a number of GCC background papers on science, economics and other issues. The GCC has the following materials currently available:

- Background on the Global Climate Coalition
- Policy Papers
- Reports and papers available for ordering
- *Climate Watch Newsletter* (Coming soon!)

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New! **Current Events in Climate Change** New!

- IPCC 1995 Synthesis Report
  The Intergovernmental Panel on Climate Change (IPCC) has finalized its 1995 Second Assessment Report on the science of climate change. You can view and download the report from the IPCC's website. You will also find the Summary for Policymakers repo rts for each of the three IPCC Working Groups.

- Upcoming Meetings of The AGBM, SBSTA and SBI
  The third session of the UNFCCC's Ad Hoc Group on the Berlin Mandate (AGBM-3), the Subsidiary Body on Scientific and Technological Advice (SBSTA) and the Subsidiary Body on Implementation (SBI) will be held February 27 - March 8, in Geneva, Switzerlan d. Documents to be discussed at these meetings can be viewed and downloaded from the UN's Information Unit on Climate Change website.

- Timetable of International Climate Activities: 1979 - 1996
  The GCC has created a cronological timetable of the major international climate change meetings over the past three decades, beginning with the first World Climate Conference and including the latest conferences under the U.N. Framework Convention on Climate Change. Hyperlinks are provided for official reports, press releases and working papers. Keep coming back for the latest meetings and links.

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***Have A Nice Day!***

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*For more information on this website*
*or other climate related resources on the Internet, contact:*
***Joshua Metz, Administrative Director***
*202/637-3190*
*email: gcc@igc.apc.org*

*For more information about the GCC, contact:*
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*Washington, DC 20004*
*PH: 202/637-3162*
*FX: 202/638-1043*

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***Last Update*: February 18, 1996**

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INTERMARKET
WEBSITE DEVELOPMENT

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# Trends in Global Greenhouse Gas Emissions

## Greenhouse Gas Emissions

According to research sponsored by the United Nations Environment Program, water vapor, which occurs naturally in the atmosphere, is the single most important greenhouse gas. It accounts for up to 90 percent of the warming that occurs when infrared radiation from the sun is trapped by greenhouse gases in the Earth's atmosphere. These gases originate from such natural sources as plant and animal respiration, volcanic activity and from the oceans. Man-made ("anthropogenic") emissions also result from human activities such as energy consumption, agriculture and deforestation.

Historically, the majority of man-made greenhouse gas emissions have come from the industrialized countries. More recently, the rate of increase in man-made emissions from these nations has slowed. This is due at least in part to tremendous improvements in the efficiency of energy consumption. At the same time, the proportion of greenhouse gases originating in the industrialized West began to drop significantly. The reason? Aside from the energy efficiency improvements just mentioned, the percentage of total global emissions from the West is rapidly declining due to the increasing greenhouse gas emissions from both developing countries and those with economies in transition.

In fact, the rate of increase in emissions from developing countries like India and China is so enormous that scientists now say emissions reduction efforts in the United States will have little impact on global emissions of greenhouse gases. Clearly, reduction efforts should continue where they make economic sense. But, this trend does pose a serious challenge for policymakers, who must be able to show that costly mitigation efforts imposed on some countries will bring meaningful global results.

## Greenhouse Gas Emissions From Developing Countries

Many developing nations and countries with economies in transition have experienced population surges and tremendous economic growth over the past two decades. Industrial sectors are growing rapidly and standards of living are slowly improving. The result has been an increase in the amount of energy these nations consume. However, the widespread use of outdated and inefficient technologies (by Western standards) has meant that increasing energyuse has outpaced economic expansion in these countries by 20 percent. [1]

Since 1970 energy consumption in developing nations has almost tripled, a rate of increase 15 times that of industrial nations, whose energy use rose only one-fifth as much as economic growth between 1973 and 1989. Developing nations today require 40 percent more energy than industrial nations to produce the same goods and services. [2]

This trend likely will accelerate as developing nations struggle to accommodate the demands of growing economies and populations. The U.N. Population Fund estimates a six-fold increase in the Earth's population over the next two hundred years. Such population increases, along with economic expansion, will result in greater energy demands. Even if per capita energy consumption remains at current levels, population growth alone will spur a 70 percent jump in global energy-use within 30 years. With high rates of economic growth, developing countries could triple their energy-use again by 2020. [3]

The inevitable result will be increased greenhouse gas emissions from developing nations. In fact, the U.N. Intergovernmental Panel on Climate Change (IPCC) estimates that by 2025, developing nations and countries with formerly centrally planned economies will contribute 68 percent of global, man-made greenhouse gas emissions, rising to as high as 76 percent within the following 25 years. By 2025, China alone will emit more carbon dioxide than the current combined total of the United States, Japan and Canada, according to IPCC projections. The U.S. Department of Energy recently announced that, collectively, developing nations are already the world's greatest emitters of carbon dioxide.

## ●Energy Efficiency and Greenhouse Gas Emissions in Industrialized Nations

In contrast to the record of developing countries, industrialized nations have made significant improvements in reducing energy intensity (i.e., energy consumption per unit of GDP) since 1973. (Comprehensive data are available through 1988.) The World Resources Institute reports that during this period, Japan's manufacturing sector decreased its energy intensity by 37 percent and the United States by 33 percent. Moreover, six European countries averaged a 29 percent reduction in energy intensity between 1973 and 1988. [4] Because these figures do not account for structural shifts toward less energy-intensive industries, overall energy performance actually improved much more - by 50 percent in the United States, 49 percent in Japan and 33 percent in Germany. [5]

The United States provides a good example of how such efficiency can yield both economic and environmental benefits. From 1973 to 1988, the United States built 20 million new homes, put 50 million more vehicles on its roads and increased its GNP 46 percent. However, energy consumption increased only 7 percent. This efficiency, resulted in both cumulative energy savings of more than $1 trillion and reductions of industrial carbon dioxide emissions (per unit of output) of 37 percent. As a whole, U.S. manufacturing reduced carbon emissions 8.1 percent while increasing production by 55.8 percent.

As these trends continue, industrialized nations will be responsible for a smaller share of global greenhouse gas emissions. By 2000, the United States and Western Europe each will contribute 19 percent of anthropogenic global greenhouse gas emissions. The IPCC estimates that these shares will drop to about 16 percent by 2015 and to 12 percent by 2050.

## ●Reducing Global Emissions

Developing countries could improve their energy efficiency and their economic competitiveness by using energy-efficient technologies currently employed by industrial nations. Investments in such technologies are a cost-effective way to reduce global greenhouse gas emissions and could yield positive economic returns.

By helping developing nations reduce the amount of energy needed to expand their industries, the United States and other industrialized countries can reduce global greenhouse gas emissions, enhance the quality of life in developing nations, and provide jobs both at home and abroad. Domestic environmental and economic policies should encourage the widespread investment and promotion of environmental technologies in developing nations.

*The Global Climate Coalition, the leading business voice on climate change, is an organization of business trade associations andprivate companies established in 1989 to coordinate business* *participation in the scientific and policy debate on the global climate change issue.*

[1] Lenssen, Nicholas. "Empowering Development: The New Energy Equation." Worldwatch Paper 111, November 1992. p. 17.

[2] 1bid.

[3] 1bid, p. 16.

[4] World Resources 1992-93. Oxford University Press, 1992. p. 21. (with U.N. Environment Programme & U.N. Development Programme).

[5] The EOP Group, Inc. "Leadership In Energy Efficiency: A Comparison Of The U.S. Versus The Other Major Industrialized Countries." March, 1993.

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Return to GCC Home Page

*This site will be updated regularly !!*

# CLIMATE CRISIS

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"Global warming, ozone depletion, the loss of living species, deforestation - they all have a common cause: the new relationship between human civilization and the earth's natural balance."

-Al Gore, US Vice President, "Earth In The Balance"

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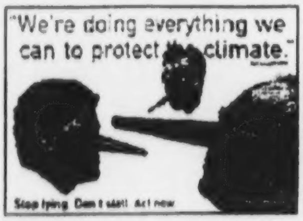
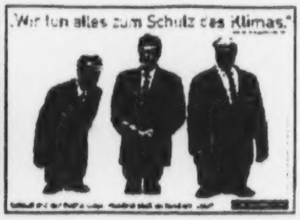
- **NEW!** Health Impacts - Global Warming and Climate Changes Endanger Human Health
- The Interactive Climate Quiz - Test your knowledge !
- The Greenpeace International Climate Campaign
- The Climate Time Bomb **Many Graphics** - slow, but worth it !
  - 1994 Update
- Frequently Asked Questions on Climate Issues
- Voice Your Concerns to President Clinton:
  The United States is the largest emitter of greenhouse gases in the world.
- Feature Reports on Climate Change
  - Antarctic Warming - Early Signs Of Global Climate Change
  - Climate Change and River Flooding
- Greenpeace at the 1995 Berlin Climate Summit
  - Greenpeace Media Information Package for the Berlin Summit
  - Greenpeace Press Releases from Berlin
  - Berlin Diary
  - 2020 Hindsight: A View of the 1995 Berlin Summit from the Year 2020
    1995 Berlin Summit - A Success
    1995 Berlin Summit - A Failure
- Does anyone out there really believe that "World leaders are doing everything they can to protect the climate"? Take a look at our billboards in Berlin. [jpg/75K]


"We're doing everything we can to protect the climate."
Stop lying. Don't stall. Act now.


„Wir tun alles zum Schutz des Klimas."

- Other Valuable Resources on Climate Issues on the Internet
- Acknowledgments

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- Return to Greenpeace International's Homepage

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This site last updated **(04/15/96)**
Send your comments regarding content to: john.mate@green2.greenpeace.org
Developed by jot. Send error reports to: tuinman@sfu.ca

# Calculating National Accountability for CLIMATE CHANGE

BY ALLEN L. HAMMOND,
ERIC RODENBURG, AND WILLIAM R. MOOMAW

Every year, human activities cause the release of more than 7 billion tonnes of carbon in the form of carbon dioxide ($CO_2$) into the atmosphere, as well as large quantities of methane and other infrared-absorbing greenhouse gases. These releases are rapidly altering the composition and heat-trapping properties of the atmosphere and may actually change the global climate. According to a recent report of the United Nations-sponsored Intergovernmental Panel on Climate Change (IPCC), these "long-lived gases would require immediate reductions in emissions from human activities of over 60% to stabilize their concentrations at today's levels; methane would require a 15-20% reduction."[1]

In February, the first negotiating sessions for a framework convention on global climate change will attempt to forge an international agreement aimed at limiting anthropogenic emissions of greenhouse gases. Such an agreement is needed urgently, given the rate at which human activity is altering the composi-

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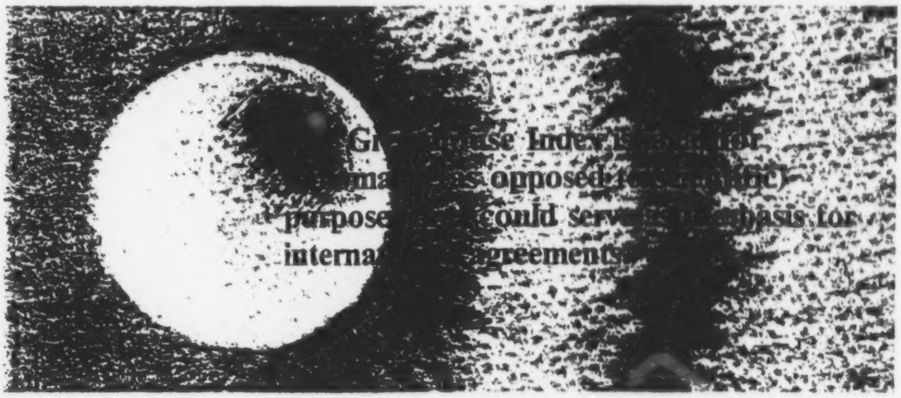
tion of the atmosphere. But before nations can agree to reduce their contributions to the potential warming of the atmosphere, they will need estimates of what those contributions are and a means of comparing relative national contributions. Neither of these needs is easy to fulfill. Emissions data, especially for developing countries, are fragmentary and often of dubious accuracy. Existing methods of comparing the contributions of different gases—although they are as accurate as is scientifically possible—contain an arbitrary element that can lead to conflicting results depending on the perspective of the analyst or country that applies them. Nonetheless, a workable accounting system for climate pollution is essential to the conclusion and enforcement of international treaties limiting greenhouse-gas emissions.



Given comprehensive estimates of the principal greenhouse-gas emissions, compiled country by country on an annual basis, and an empirical measure of the effective heat-trapping ability, or radiative forcing, attributable to each gas, one can create a "Greenhouse Index" that facilitates comparison of national contributions to the warming potential of the atmosphere. The method that gives rise to the index is straightforward and readily applied by policymakers. Thus, the Greenhouse Index is ideal for diplomatic (as opposed to scientific) purposes and could serve as the basis for international agreements.

Detailed estimates of emissions of $CO_2$, methane ($CH_4$), and chlorofluorocarbons (CFCs)—the most important greenhouse gases—from 146 countries' major anthropogenic sources have been compiled from the data base of the World Resources Institute and other sources. Worldwide, the largest source of $CO_2$ in 1988 was the combustion of solid fossil fuels, largely coal. In descending order, the next largest contributors were combustion of oil and other liquid fossil fuels; permanent conversion of forested land to other uses; combustion of gaseous fossil fuels, mostly methane; cement manufacture; and flaring of natural gas during oil extraction. The largest sources of $CH_4$ emissions were wet rice cultivation and domestic livestock, but the anaerobic fermentation of solid wastes, production of coal, and production and transportation of natural gas also released significant quantities of methane. The sources of CFCs—mostly CFC-11 and CFC-12—include emissions from leaky refrigerators and air conditioners, electronic circuit board cleaning, and foaming plastic insulation.

In 1988, the estimated global emissions of these gases totaled 7.7 billion tonnes of carbon (as $CO_2$), 260 million tonnes of $CH_4$, and 770,000 tonnes of CFC-11 and CFC-12. Other infrared-absorbing gases not accounted for here include tropospheric ozone, nitrous oxides, and other CFCs, but these gases probably represent only about 15 percent of all anthropogenic greenhouse-gas releases at present. Inclusion of these other gases—if sufficient information on their sources were available—probably would not significantly alter the country rankings in the Greenhouse Index.

### Calculating a Greenhouse Index

Carbon dioxide is emitted by volcanos and seafloor vents, as well as by cars and power plants. It is absorbed by plants for use in photosynthesis and stored in tree trunks and other living biomass and in plant debris in the soil. $CO_2$ is also absorbed in the oceans, where a portion is converted to calcium carbonate by marine organisms such as coral and ultimately buried in seafloor sediments. This complex, natural biogeochemical cycle is disturbed by anthropogenic emissions of $CO_2$ in ways that are not fully understood at present. Indeed, the effective lifetime of a $CO_2$ molecule in the atmosphere is not accurately known. Methane, too, has natural sources and sinks and enters into chemical reactions in the atmosphere that may have indirect effects on the potential warming that are larger than the direct effects. Therefore, estimating the relative contributions [illegible] these gases to the radiative forcing [illegible] the atmosphere is extremely difficult.

Two basic methods of estimating contributions have been proposed. The first, adopted by IPCC, estimates the future contributions of a given gas by calculating its global warming potential (GWP). Applying this method, however, requires adopting an arbitrary future time period over which the calculation is carried out and implicitly requires assumptions about how atmospheric conditions will change over that time period because the radiative efficiency of greenhouse gases varies with their concentration.

The alternate method proposed here is empirical in that it is based on the behavior of the atmosphere. The observed increase in the amount of a greenhouse gas present in the atmosphere is compared to the estimated anthropogenic emissions of that gas in a given year. This ratio, known as the airborne fraction, can be thought of as an empirical, instantaneous measure of the effecti[illegible] lifetime of the gas. It is not in any sens

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a measure of molecular lifetime but, rather, a measure that balances the effects of present and past emissions and the operation of natural cycles. Multiplying a gas's airborne fraction by its present radiative efficiency (as compared to that of $CO_2$) gives an instantaneous greenhouse forcing contribution (GFC). (The radiative efficiencies used for this accounting are 15.8 kilograms of carbon equivalent per kilogram of $CH_4$, 1,083 kilograms of carbon equivalent per kilogram of CFC-11, and 1,568 kilograms of carbon equivalent per kilogram of CFC-12.[2]) Multiplying greenhouse gases' GFCs by a country's actual emissions of those gases and then adding up the resulting products yields a Greenhouse Index score for the country. The calculation of a country's relative warming contribution of each gas is mathematically equivalent to allocating to each country a share of the observed atmospheric increase in proportion to its share of global anthropogenic emissions, if one assumes that all of the increase is attributable to anthropogenic emissions. Thus, countries can be ranked according to their Greenhouse Index scores, which are measured in tonnes of carbon equivalent.

In 1988, the observed increases over the previous year in the concentrations of the major greenhouse gases were 2.6 parts per million for $CO_2$, 24 parts per billion for $CH_4$, 16 parts per trillion for CFC-11, and 18 parts per trillion for CFC-12. These higher concentrations imply increases of 5.5 billion tonnes of $CO_2$, 68 million tonnes of $CH_4$, and 770,000 tonnes of CFCs. These were the empirical net additions of the gases to the atmosphere in 1988, taking into account both anthropogenic and natural sources and sinks. It is plausible to attribute all of the net additions to anthropogenic sources because the atmospheric concentrations of the gases were stable (indeed, zero for CFCs) and the natural cycles presumably were in balance in the millennia immediately prior to the Industrial Revolution. Therefore, for the purposes of this analytic scheme, increased concentrations of greenhouse gases in the atmosphere are attributed to human activities.

Although this method accounts for the differing lifetimes of the greenhouse gases and, hence, for their differing greenhouse impacts, it does not predict those impacts as the method based on global warming potentials attempts to do. Likewise, the GFC method ascribes the airborne fraction of each gas to current-year emissions, but prior histories of emissions and of the natural cycles also play a role. Nonetheless, this method has the advantage that it is empirical and not based on assumptions about the future state of the atmosphere. Thus, it links observable current results to policy actions in a concrete fashion that may be appropriate to international agreements.

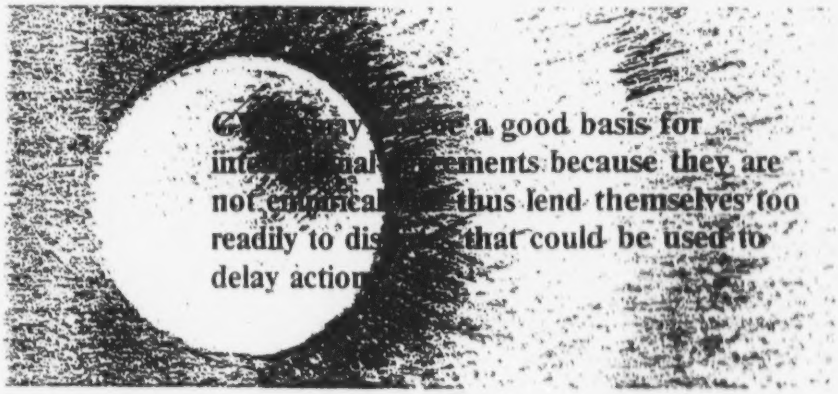
A greenhouse index can also be calculated according to the GWPs adopted by IPCC. (A country's score would be the sum of the products of its emissions of each greenhouse gas multiplied by each gas's GWP.) However, the results depend on the arbitrary time period over which the heating effects of the gases are calculated; quite different GWPs result when calculations are made for 20, 100, and 500 years. Although appropriate for scientific purposes and for comparing the greenhouse effects of alternate technologies, GWPs may not be a good basis for international agreements because they are not empirical and thus lend themselves too readily to disputes that could be used to delay action. Equally troubling is the uncertainty in GWP values, which is attributable to, among other things, the unknown lifetime of $CO_2$. Future revisions of GWP values (which might change by a factor of two) may be required as knowledge of the carbon cycle improves, and revised values could materially affect a country's obligations under a greenhouse convention.

The GFC method has one additional advantage: By focusing on the instantaneous change in radiative forcing of the atmosphere, it emphasizes the rate of warming. The rate of climate change, as much as the eventual magnitude, poses the greatest difficulties to ecosystems and human societies.

## National Accountability

The 1988 Greenhouse Index scores for the 20 largest countries are shown in Table 1 on page 14. The United States leads the list with 17.1 percent of all 1988 contributions. The European Community, if considered as a single entity, would rank third with about 12 percent. Brazil, which had significantly decreased deforestation, dropped from third in 1987 to fourth in 1988.[3] Overall, industrialized countries accounted for 54 percent of all anthropogenic greenhouse-gas emissions in 1988. Developing countries, therefore, accounted for 46 percent of the world total—a far larger proportion than generally has been recognized.

Most sources of climate-affecting pollution are concentrated in a relatively small number of countries, which include both industrial and developing, both free-market and planned econo-



**G[illegible] may [illegible] a good basis for inte[illegible]nal [illegible]ements because they are not empirical [illegible] thus lend themselves too readily to dis[illegible] that could be used to delay action**

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## TABLE 1
## THE 20 LARGEST CONTRIBUTORS TO 1988 GREENHOUSE FORCING

| Rank | Country | Total net additions (million tonnes of carbon equivalent) | Percentage share of atmospheric greenhouse-gas increase | Net per-capita additions (tonnes of carbon equivalent) |
|---|---|---|---|---|
| 1 | United States | 1,300 | 17.1 | 5.4 |
| 2 | USSR | 1,000 | 13.5 | 3.6 |
| 3 | China | 620 | 8.1 | 0.6 |
| 4 | Brazil | 430 | 5.7 | 3.0 |
| 5 | India | 350 | 4.6 | 0.4 |
| 6 | Japan | 280 | 3.6 | 2.3 |
| 7 | Indonesia | 220 | 2.9 | 1.3 |
| 8 | West Germany | 210 | 2.7 | 3.4 |
| 9 | United Kingdom | 180 | 2.4 | 3.2 |
| 10 | Myanmar | 160 | 2.1 | 4.0 |
| 11 | Italy | 140 | 1.8 | 2.4 |
| 12 | France | 130 | 1.7 | 2.3 |
| 13 | Canada | 130 | 1.6 | 4.8 |
| 14 | Mexico | 120 | 1.6 | 1.5 |
| 15 | Poland | 110 | 1.4 | 2.9 |
| 16 | Thailand | 95 | 1.2 | 1.7 |
| 17 | Nigeria | 90 | 1.2 | 0.8 |
| 18 | Colombia | 86 | 1.1 | 2.9 |
| 19 | Spain | 83 | 1.1 | 2.1 |
| 20 | Australia | 82 | 1.1 | 5.0 |
|  | **World** | **7,700** | **100.0** | **1.5** |

mies. Of the six countries that emitted the most greenhouse gases in 1988—together contributing more than 50 percent of the incremental atmospheric burden—three had heavily industrialized economies and three did not. The 20 largest emitters together contributed more than 75 percent of all additions to the atmospheric heating potential in 1988. By continental area, non-Soviet Asia was the largest source, contributing 31 percent of the total, while North American sources contributed 21 percent. The large potential for future increases in greenhouse-gas emissions, however, means that action on the part of many countries will be required to stabilize or reduce these emissions and diminish the threat of global warming. Present national commitments to reduce emissions are discussed in the box on page 15.

It is also pertinent to compare national contributions on a per-capita basis. The map in Figure 1 on pages 34 and 35 grades countries according to their per-capita 1988 Greenhouse Index scores. High rates of energy production and use accounted for the elevated per-capita standings of the United States, Canada, Australia, East Germany, and a number of small oil-producing states. High rates of deforestation accounted for the standings of Laos and the Ivory Coast. A second group with less elevated but still high per-capita rankings includes many European countries and some Asian, African, and Latin American countries experiencing rapid industrial growth or high rates of forest loss. The third group, whose net 1988 per-capita additions fell between 1.5 and 2.9 tonnes of carbon equivalent, includes such relatively energy-efficient countries as Switzerland and Japan, as well as countries at early stages of industrial development. France, because of its large commitment to nuclear power rather than fossil fuel combustion, is also found in this group. The fourth and fifth groups contain those countries that, like China and India, had per-capita Greenhouse Index scores below or substantially below the world average of 1.5 tonnes of carbon equivalent per capita.

Per-capita figures can also be looked at as an indication of how much greenhouse-gas emissions and the greenhouse forcing function of the atmosphere might increase if developing countries significantly increase their per-capita emissions or their populations. China and India, for example, had net per-capita additions of 0.6 and 0.5 tonnes of carbon equivalent, respectively, compared with 5.3 tonnes per capita for the United States. Increasing to the world average the per-capita contributions of all countries currently below that figure would raise worldwide annual additions to the atmosphere's greenhouse forcing function by 38 percent—an additional 3 billion tonnes of carbon equivalent per year.

### Data Sources

Countries vary in their ability to measure or estimate climate input parameters, in their application of standard methods and definitions, and in the organizational structures and resources they can bring to bear on data collection and analysis. Measures of accuracy are rarely available for data assembled on an international scale, and data often are not generated with standard survey techniques, in which case accuracy measures are, in fact, irrelevant. The accuracy and timeliness of most national-level data bases are of exceptionally low quality.

In recognition of this reality, the map in Figure 1 is based on Greenhouse Index scores calculated to only two significant figures, which still give a fair picture of relative levels of greenhouse-gas emissions. A difference in rank between two countries, however, is only as important as the absolute difference between them. The countries of the world fall naturally into several significant classes, but arguments over rank within a class are of limited value.

Among the data used in the calculation of the Greenhouse Index, the total emissions of $CO_2$ from fossil fuel consumption and cement manufacture are the best documented and most dependable.[3] Scientists at the Carbon Dioxide Information Analysis Center in Oak Ridge, Tennessee, annually calculate

## COMMITMENTS TO REDUCE GREENHOUSE-GAS EMISSIONS

At least 23 countries have announced plans or commitments to stabilize or reduce greenhouse-gas emissions. These commitments include both revisions to the Montreal Protocol on Substances That Deplete the Ozone Layer, which calls for phasing out production and use of CFCs (chlorofluorocarbons) by 2000, and, in some countries, additional commitments to limit or reduce carbon dioxide emissions.

The Greenhouse Index can be used to gauge the relative effects of these national commitments. If one assumes that these plans are fully implemented now, and if the greenhouse effects of CFC replacements (which for some will be significant, particularly in the short term) are neglected, the reduction in current national contributions to the radiative forcing of the atmosphere can be calculated. Overall, the announced plans and commitments of the 23 countries, if they had been in effect in 1988, would have reduced total heating additions to the atmosphere by 13 percent. Planned changes in national contributions vary widely (see table below).

**ESTIMATED DECLINE IN GREENHOUSE INDEX SCORES FROM 1988 TO 2005**

| Country | Percentage decline[a] |
|---|---|
| Australia | 34.9 |
| Austria | 46.5 |
| Belgium | 34.7 |
| Canada | 19.8 |
| Denmark | 43.4 |
| Finland | 28.2 |
| France | 44.5 |
| Greece | 42.4 |
| Iceland | 20.1 |
| Ireland | 33.2 |
| Italy | 43.5 |
| Japan | 26.0 |
| Luxembourg | 19.6 |
| Netherlands | 37.6 |
| New Zealand | 26.8 |
| Norway | 8.5 |
| Portugal | 57.4 |
| Spain | 48.3 |
| Sweden | 25.6 |
| Switzerland | 43.6 |
| United Kingdom | 33.2 |
| United States | 5.1 |
| West Germany | 45.8 |

[a] Based on planned stabilization, decreases, or increases in greenhouse emissions and total recycling of CFC-11 and CFC-12 in 2005.

these figures from data supplied by the United Nations Statistical Office and the U.S. Bureau of Mines. The scientists believe that their emissions calculations fall within 10 percent of actual emissions.[5] By the standards of international data accounting, such accuracy is outstanding. The center's estimate of $CO_2$ emissions resulting from natural gas flaring was reduced for this calculation to account for gas actually vented as methane.

Data from land-use change are based on the permanent conversion of forest to other uses, especially in tropical and neotropical countries. Deforestation, by this definition, does not include the renewable or potentially renewable use of forests for logging or shifting cultivation. However, areas that are logged in the process of conversion or are permanently converted from forest fallow to cropland are included.

The deforestation data used to calculate the 1988 Greenhouse Index are estimates from the United Nations Food and Agriculture Organization's (FAO) 1988 update of its 1980 tropical forestry assessment, except for the data on nine countries for which there are recent credible studies of deforestation.[6] The largest amount of forest loss occurred in Brazil. Although the precise rate of deforestation within the Amazon basin is disputed, an estimated loss of 4 million hectares of closed forest—a 40-percent decrease from 1987 estimates—is reasonable. Brazil has moved actively in recent years to reduce its deforestation rate, and 1989 deforestation in the Brazilian Amazon is reliably estimated at 2.6 million hectares, a further 40-percent decline that will lead to a significant decrease in Brazil's Greenhouse Index rank.

Emissions of $CO_2$ caused by deforestation in 1988 were calculated as though all emissions occurred in 1988, but only a portion would actually have been released during that year. Releases from slow oxidation begun by actions taken in previous years were also occurring in 1988 but are not accounted for in the estimates. In effect, the estimates include the net present values of deforestation that took place in 1988. Carbon stocks in forests were calculated from Richard A. Houghton's estimates of carbon emissions.[7] His estimates explicitly include both the sequestering of elemental carbon in the soil (in the form of charcoal) and the release of carbon (through the oxidation of organic matter) from soil exposed as a consequence of deforestation. Data on carbon releases from the conversion of open forests and forest fallow were taken from work by Houghton and others.[8] Although not necessarily derived from areas of deforestation, the carbon content of saw and veneer logs produced in 1988 was subtracted from calculated carbon emissions to account for the carbon sequestered in durable goods in each country.[9]

Estimates of anthropogenic emissions of methane were based on several sources of information.[10] Methane emissions data from municipal solid waste were derived from the work of Heinz G. Bingemer and Paul J. Crutzen, and data on emissions from domestic animals were based on the work of Jean Lerner, Elaine Mathews, and Inez Fung, who estimated animal methane production based on energy intake under several different management methods and feeding regimes.[11] Data on methane emissions from coal mining were based on the methane content of the mass of coal (anthracite/bituminous, subbituminous, and lignite) mined in each country.[12] The methane content of coal varies according to its depth and the degree of coalification.

Methane also is emitted from the artificial wetlands formed for rice cultivation. A country's or region's total area of $CH_4$-emitting rice production was calculated by subtracting upland (dry land) rice-growing areas from FAO data on the total area of rice production.[13] Thus, the data for wet rice cultivation included $CH_4$ emissions from irrigated, rain-fed, floating, and tidal rice production systems. Methane emissions per hectare of rice paddy were determined by monitoring the methane production of an Italian rice paddy over a three-year period.[14] Methane yields were calculated using the mid

(continued on page 33)

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### Climate Change

*(continued from page 15)*

ranges of daily emissions and growing periods estimated separately for temperate rice-producing countries and tropical rice-producing countries. Methane yields also were adjusted to account for areas where two rice crops are grown each year.

Substantial quantities of methane are vented to the atmosphere in the course of oil production; these are estimated at 25 percent of the amount that is flared.[15] $CH_4$ emissions during natural gas production were estimated at 0.5 percent of production.[16] Recent modeling research has dramatically lowered earlier estimates of $CH_4$ leakage from pipelines to no more than 1 percent of total production in the United States and to no more than 1.7 percent in the Soviet Union, though careful surveys have not been done.[17] $CH_4$ emissions from Western European distribution systems were also estimated at 1 percent of production because they were thought to be slightly higher than those of the United States, and emissions from Eastern European countries and the rest of the world were estimated at 1.7 percent because their situations were thought to be similar to that of the Soviet Union.[18]

Approximate CFC-11 and CFC-12 emissions for 1988 were estimated using 1986 CFC-use data for 18 countries[19] to calibrate a separate ranking of all countries according to their relative CFC use per capita.[20] The result was an assignment of more precise per-capita CFC-use levels for each country. These estimates were used to assign each country a share of total emissions. (The total of these shares was in reasonable agreement with published world CFC-use totals.[21]) Many governments and international agencies consider CFC manufacture and use to be confidential, although it is doubtful whether any agency has sound information on a global basis. Large manufacturers of CFCs probably have fairly accurate market data for each country, but such data are proprietary and, thus, inaccessible. The method used here produced some anomalies. Portugal, for example, was assigned the same per-capita level of CFC use as the rest of the European Community, 0.8 kilograms, which the community reported as the level of all its member countries combined. If Portugal had not been a member, its CFC use would have been estimated at 0.2 kilograms per capita.

### Political Implications

Despite the uncertainties inherent in a data set encompassing 146 countries, the analytic scheme proposed here provides a realistic and workable method of making national comparisons and tracking significant trends in the anthropogenic greenhouse-gas emissions. In particular, the relative rankings of countries based on the 1988 Greenhouse Index are strong enough to withstand reasonable changes in data or assumptions. A 20- to 30-percent change in the amount of carbon released per hectare of deforestation, for example, causes no significant change in country rankings, and neither does an 8-percent reduction in CFC use.

A measure of national accountability for contributions to the greenhouse effect such as the Greenhouse Index is needed to inform the actions of inter-

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national and, especially, national decisionmaking. It is at the level of the nation-state that negotiations will occur and questions of impact, equity, and mitigation arise. And it is also at the level of the nation-state that laws will be written and implemented to enforce any international agreement. Measures of greenhouse-gas emissions that fail to assign responsibility by country will have little impact on national actions. By assigning responsibility, this index should promote discussion, argument, and action.

The implications of this analysis for environmental policy are clear. In 1988, the world significantly increased the greenhouse forcing of the atmosphere by emitting the equivalent of 7.7 billion tonnes of carbon to the air. The additional heating potential added per person was the equivalent of 1.5 tonnes of carbon. The sources of these additions are spread widely among both industrialized and developing nations, among free-market and planned economies. Virtually all nations that are major sources of greenhouse gases will have to reduce their emissions if the heating potential of the atmosphere is to be reduced. If per-capita greenhouse-gas emissions rise significantly in developing countries in response to legitimate aspirations for growth and equity, the effect on rates of greenhouse forcing could be enormous. Thus, industrialized countries have a powerful incentive to take the lead in limiting greenhouse-gas emissions wherever possible and to assist developing countries in doing the same.

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## NOTES

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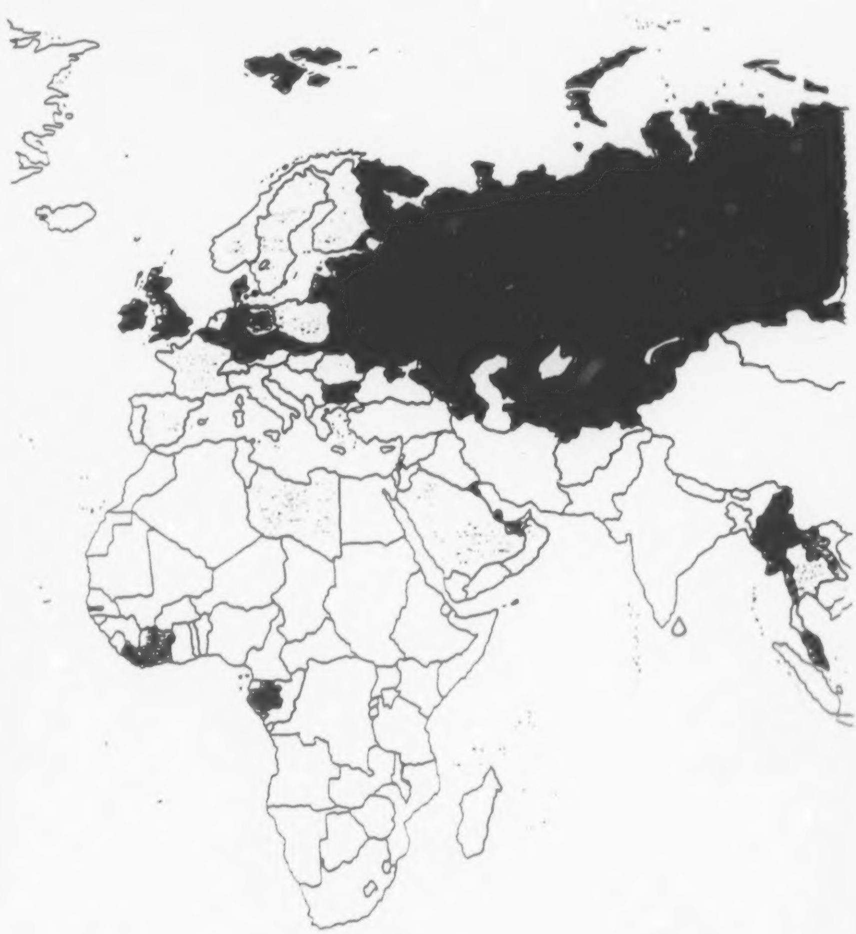
**FIGURE 1. 1988 per-capita contributions to greenhouse forcing.**



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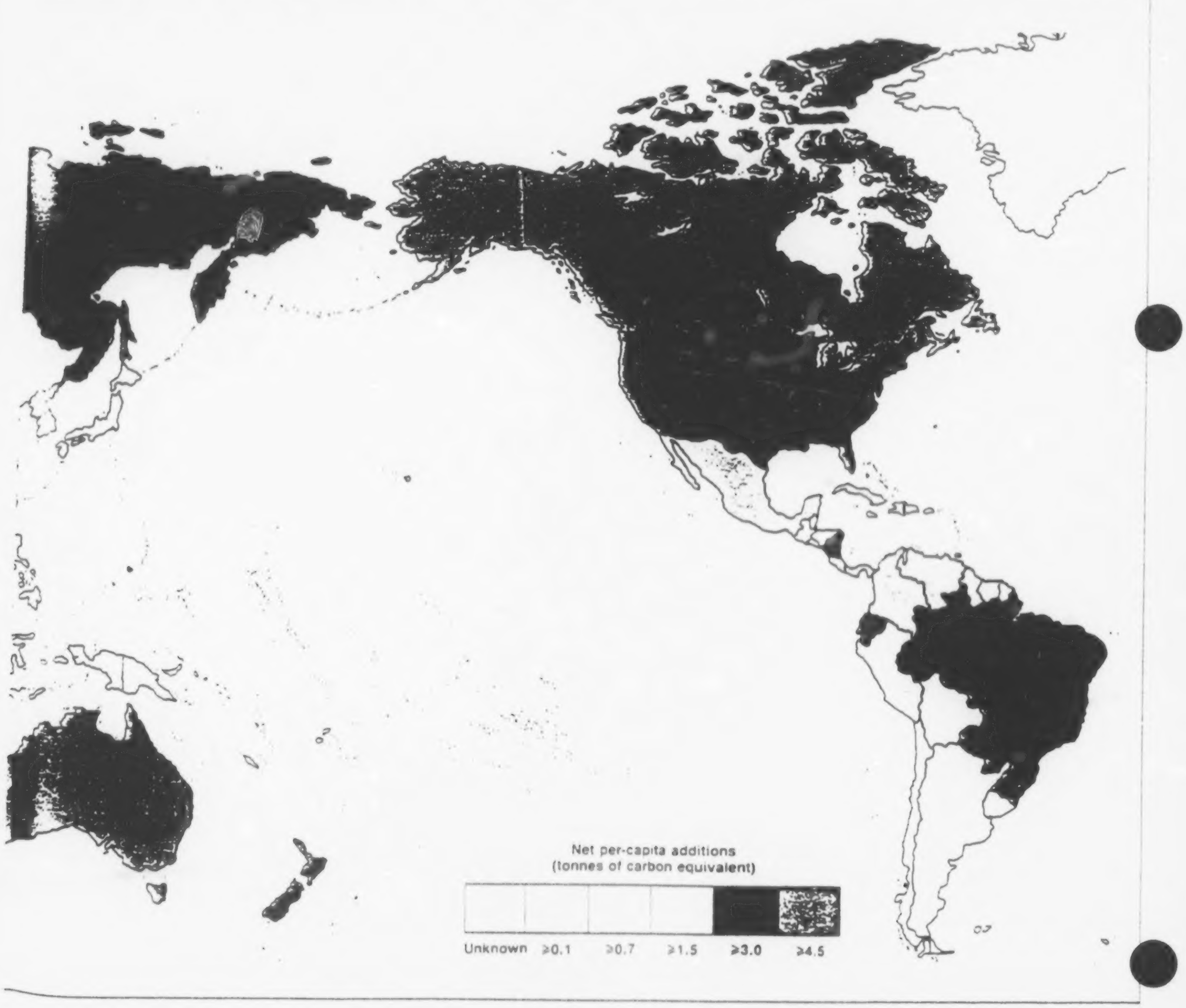

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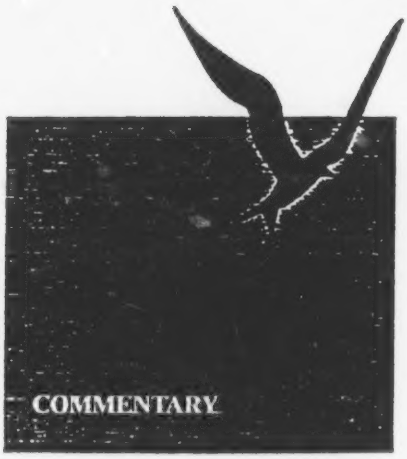

# overview

## THE GREENHOUSE INDEX

The Greenhouse Index proposed by Allen Hammond, Eric Rodenburg, and William Moomaw in the last issue of *Environment* is but one of several plausible approaches for designing greenhouse-gas indices or for "assigning accountability" for greenhouse-gas emissions. In their selection of simplifying assumptions, the authors have made important choices that could be made more appropriately after broader discussions of the ethical and political uses of alternative emissions assessments. By estimating emissions for the current period only and by the immediate heating effect only, the authors have introduced a bias in the time frame of their emissions calculations that may work to the disadvantage of developing countries.

Any greenhouse index that ranks countries by current, rather than cumulative, emissions will find developing countries to be more "accountable" for global warming than would an index that includes historical emissions of carbon dioxide ($CO_2$) and chlorofluorocarbons (CFCs), which continue to trap heat in the atmosphere decades after their release. For example, the authors' index lists Indonesia as the seventh greatest emitter. Its high ranking is due largely to $CO_2$ emissions from land-use changes, especially deforestation. The country's relative ranking would decline, however, if its emissions from earlier decades preceding the accelerated deforestation were included in the calculation and compared with historical emissions from an industrialized country that no longer depletes its forest stock. This example is not a special case. An earlier analysis of greenhouse-gas emissions by country, which was based on $CO_2$ emissions, yielded very different rankings for a broad range of countries, depending on the time frame considered—current or cumulative emissions.[1]

Expressing emissions to the atmosphere as net contributions weighted by the immediate heating effect, or instantaneous greenhouse forcing contribution (GFC)—the approach taken by the authors—narrows the focus to the impact of current emissions on today's atmosphere. By neglecting to consider the atmospheric residence time of the different greenhouse gases currently emitted, which is taken into account when carbon equivalents are expressed as global warming potentials (GWPs), the method ignores the long-term warming effect of today's emissions. The authors' GFC-based approach holds the countries that produce greater quantities of the longer-lived gases, such as $CO_2$, less accountable than does a $CO_2$-equivalent index based on global warming potential. One consequence of the focus on the immediate effect of current emissions may be a bias against the countries that produce more of the shorter-lived greenhouse gas—methane ($CH_4$). These countries may include many developing countries where agricultural activities, such as $CH_4$-emitting rice and livestock production, figure more prominently than the industrial sector, which is the primary source of $CO_2$ and CFC emissions.

As a baseline assessment against which countries may set targets for future reductions, the approach taken by the authors is a useful first step. The assessment could be made more comprehensive by considering additional anthropogenic sources and sinks for the gases that they inventory. These sources include biomass burning, which produces significant quantities of methane; soil disturbances, which increase the net flux of nitrous oxide; and reforestation and plantation growth, which absorb significant quantities of carbon.

The Stockholm Environment Institute is completing the Greenhouse Gas Scenario System, an assessment tool that includes a comprehensive inventory of nitrous oxide, carbon monoxide, and CFC emissions in addition to the four gases included in the authors' index. This computerized system includes a structure for projecting future emissions under a broad range of socioeconomic assumptions and policy parameters that are designed to be transparent to a broad range of users. Emissions may be expressed in carbon-equivalent units by either global warming potential or instantaneous radiative forcing. The scenario system will be used in conjunction with data bases of historical $CO_2$ emissions. Thus, this assessment tool offers nations a range of options in analyzing greenhouse-gas emissions using various accounting indices.

It is important that the alternative assessments offered by the research community become available to the official delegates sooner, rather than later, in the negotiation process, when these questions are more likely to delay action. Most likely, however, emissions estimates offered by the Stockholm Environment Institute, the World Resources Institute, and others in the research community may not have the immediate diplomatic use suggested by Hammond and his colleagues because accountability is ultimately a political and ethical, as well as a technical, question.

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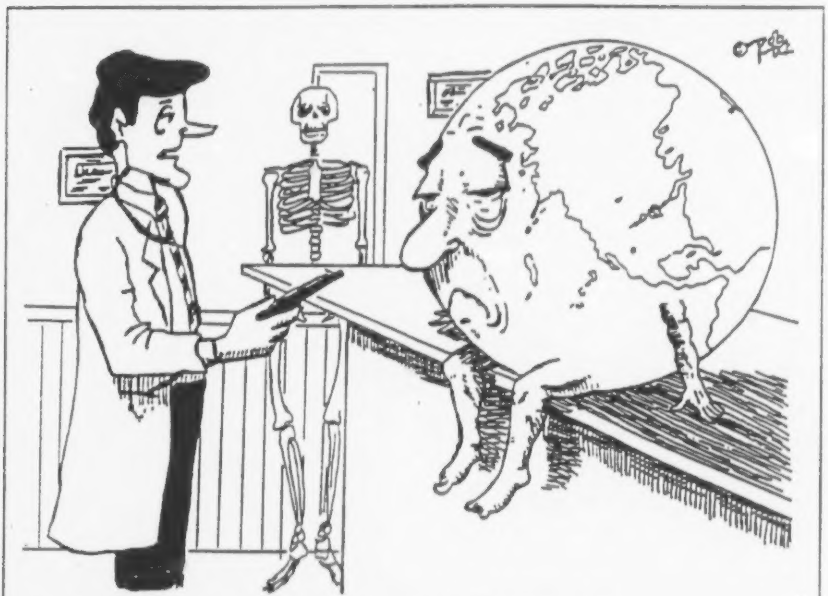
1. S. Subak and W. C. Clark, *Accounts for Greenhouse Gases: Towards the Design of Fair Assessments* (Stockholm, Sweden: Stockholm Environment Institute, 1990).



*"I'm sorry, but all of the tests conclusively show that you have a chronic case of civilization."*

IN LAST MONTH'S ISSUE, Allen Hammond, Eric Rodenburg, and William Moomaw sought to define a quantitative measure of the relative contribution of each nation to the growing anthropogenic greenhouse effect. Their measure, the "Greenhouse Index," includes impacts of $CO_2$, $CH_4$, and CFCs and can be used to estimate the effectiveness of programs to decrease emissions. The overall goal of the exercise is to assign responsibility for global greenhouse-gas emissions to "promote discussion, argument, and action." The authors claim that their Greenhouse Index offers significant advantage over the more commonly used global warming potential indices that are employed in the recent report by the Intergovernmental Panel on Climate Change (IPCC).

I believe that the authors have made a significant contribution to the debate and to discussions about national accountability, but a contribution that is different, perhaps, than what they intended. Specifically, their claim that their Greenhouse Index is clearer, more useful, and more empirically based than the GWP indices is not convincing, but the background work that they have invested in assigning emissions to nations is fairly original and comprehensive.

The authors' Greenhouse Index approach could be improved. In the process of offering suggestions, it may become clear why the claim of superiority of the index over GWPs is unconvincing, but I am not trying to defend the IPCC report. After all, IPCC did not invent the GWP concept but only used it. Before being adopted as a basis for international agreements, the Greenhouse Index calculation should be spelled out more clearly. A few equations would permit us to see how the final results are obtained. For example, I deduce that the airborne fractions used to calculate the greenhouse forcing contributions are 0.6, 0.14, and 1.0 for $CO_2$, $CH_4$, and CFCs, respectively, but these values are never stated. If my numbers are correct, the derivation is not too different from starting with atmospheric residence times of 60 years, 10 years, and 100 years for $CO_2$, $CH_4$, and CFCs, respectively.

The quoted annual rates of increase for 1988 that are used in the derivation are strange. I know of no evidence that the atmospheric concentration of $CH_4$ increased by 24 parts per billion; 14 to 17 parts per billion is more accurate. Also, to stabilize $CH_4$ concentrations would require only a 10 percent reduction of sources, not 15 to 20 percent as is claimed by the authors (and in the IPCC report), and annual $CH_4$ emissions are more than 400 million tonnes, not 260 million. I suspect that these changes would not cause the authors' conclusions to change, but the presentation would be more credible.

Further research is needed to reduce some very troubling uncertainties in current knowledge of the flows of greenhouse gases. For example, there is real doubt about how large the rice-paddy and biomass-burning sources of methane are. Rice paddies may emit anywhere between 25 to 170 million tonnes of $CH_4$ per year. Data from various field studies show striking differences, probably caused by variations in agricultural practices such as soil preparation and water management. Similarly, there are probably large differences in methane emissions from coal mines and gas exploration and leaks. It also should not be forgotten that the reasons for a $CO_2$ airborne fraction of 0.6 are not very clear; many questions remain about the carbon cycle. Moreover, does a formulation sound reasonable if it neglects the nature of very long-lived substances? Any new synthetic chemical with a lifetime of 1,000 years would be treated the same as, say, CFC-11, which has a lifetime of 70 years, in the authors' formulation.

Finally, some generalization of the treatment might be needed. For example, a very interesting complication arises if we think of negative greenhouse forcing such as that from pollution-derived sulfate aerosol particles in the troposphere. It is plausible that the slower warming of the Northern Hemisphere is due to sulfur from the combustion of fossil fuels.[1] When one tries to define a basis for international accountability, should one include credits for negative delta-Q values?[2] Should the shorter residence times for sulfate particles enter into the equation? These questions require attention and the Greenhouse Index of Hammond, Rodenburg, and Moomaw may have to be generalized. Also, how does one account for energy consumed in one nation for another—say, when one nation produces nitrogen fertilizer that is used elsewhere? How does one allow for objective measures of the greenhouse impacts of devices, such as refrigerators, that might consume less energy if they could be insulated with CFC-blown foams instead of poorer insulation?

*Further research is needed to reduce some very troubling uncertainties in current knowledge of the flows of greenhouse gases.*

International agreements to limit emissions of greenhouse gases will probably require several different measures of effectiveness and political fairness. The authors have not convinced me to adopt only their index, but they have accelerated progress toward such measures.

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[1] T. M. L. Wigley, "Possible Climate Change due to $SO_2$-Derived Cloud Condensation Nuclei," *Nature* 339 (1989):365–67; and R. J. Charlson, J. Langner, and H. Rodhe, "Sulphate Aerosol and Climate," *Nature* 348 (1990):22.

[2] R. E. Dickinson and R. J. Cicerone, "Future Global Warming from Atmospheric Trace Gases," *Nature* 319 (1986):109–15.

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A SYSTEM OF CALCULATING national accountability for greenhouse-gas emissions is clearly desirable. As part of an international agreement, mechanisms for monitoring and enforcing compliance and for resolving disputes must rest on sound knowledge of national contributions to global warming. Even if no global climate convention is signed, accurate greenhouse accounts could help in smaller multilateral agreements. Moreover, by making national behavior more transparent, a credible system of international greenhouse accounts could indirectly pressure nations to reduce their greenhouse-gas emissions.

The salient issue is how to construct such an accounting framework. Two of the most critical aspects of greenhouse accounting are the comparability of emissions of different greenhouse gases and the accountability of nations for those emissions. On both counts, the system proposed by Allen Hammond, Eric Rodenburg, and William Moomaw in last month's *Environment* is substantially weaker than the authors admit.

The authors correctly criticize the use of a global warming potential because of the extreme scientific uncertainties and complexities that affect the weighting of greenhouse gases. They also correctly argue that GWPs are flawed because of arbitrary assumptions related to the different atmospheric lifetimes of gases and the time horizon over which GWPs are integrated.[1] This question of intertemporal comparisons remains a fundamental problem with comparability because of the relative value of present and future costs and benefits and because of ambiguities regarding the complex atmospheric residence time for $CO_2$.

However, by using the observed annual increases in emissions as a quasi-indicator of atmospheric lifetime, the authors have constructed a system that is inherently unable to account for future greenhouse forcing from current emissions. This inability creates at least two problems. First, it is highly unlikely that the pattern of future emissions will follow past trends, especially in the case of fossil fuel emissions of $CO_2$.[2] Although changes in the atmospheric concentration of $CO_2$ will reflect past as well as contemporary emissions, the authors' accounting assigns all of the blame to contemporary emitters.

The second problem is that, by assuming that all of the observed increase in atmospheric concentrations of greenhouse gases is due to anthropogenic emissions, the accounting system is vulnerable to the natural variability of the biogeochemical cycles over

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time. This vulnerability is especially problematic for control strategies such as emissions taxes or tradeable emissions permits, which are highly sensitive to changes in the accounting system. If such market mechanisms are intended to create long-term incentives to reduce greenhouse emissions (including incentives to emit more benign greenhouse gases), then the incentives presumably should be as stable and realistic as possible.

Thus, while GWP proponents have been much criticized, the proposed Greenhouse Index does not further the debate, especially on the difficult issue of intertemporal comparisons. Because it obscures the differential long-term consequences of present emissions, the Greenhouse Index probably represents an unfortunate step backward.

Hammond and his colleagues deserve credit for assembling and adjusting many of the dispersed data sources for greenhouse-gas emissions. Uncertainty is pervasive, however. For example, their estimates of $CH_4$ emissions from wet rice production are based on estimated rates of emissions measured from an Italian rice paddy and applied to worldwide estimates of the area under cultivation (with some corrections). But emission rates depend on numerous factors such as moisture, soil type, light, crop rotation, and fertilizer types and application and, as is amply evident in the scientific literature (including the paper cited by the authors[3]), may vary by a factor of three. In turn, these facors introduce uncertainties into accountability when the limited number of emissions rate measurements are applied globally. Moreover, the authors do not appear to have used any emission rates measured under growing conditions common to India, where one-fifth to one-quarter of the world's rice is cultivated.

Similar arguments exist for most of the other $CH_4$ sources and for the deforestation sources of $CO_2$. For many of the sources of greenhouse gases, the scientific community is a long way from building a global data base of national emissions that is ready for policy application. This critical aspect of greenhouse acceptability is obscured because Hammond, Rodenburg, and Moomaw provide no quantitative discussion of the uncertainties except in the case of fossil fuel $CO_2$ emissions, which are, by far, more accurately estimable than any of the anthropogenic $CH_4$ sources.

Nonetheless, the authors claim the rankings are robust against "reasonable" changes in data or assumptions. However, the apparent strength of the Greenhouse Index is an artifact of the authors' methodology, which allocates all of the observed annual increase in gas concentrations to all of the estimated sources, regardless of their uncertainty. Thus, the accounts balance by assumption, although the geophysical evidence does not warrant such a robust balance calculated "bottom-up" from nation-by-nation estimates. Indeed, "top-down" accounting of $CH_4$ emissions underscores that uncertainties are a factor of two or greater for many sources.[4] Such uncertainty suggests that the actual, perceived, reported, and enforced levels of emissions may be quite different. Imagine trying to enforce or obey income taxes or speed limits with such a range of uncertainty.

The accounting uncertainties and complexities hardly justify abandoning hope for an accounting system, and the arguments above should in no way be construed as an attack on the scientific research programs under way to collect emissions measurements and piece together the puzzle. My concern is that Hammond, Rodenburg, and Moomaw seem preoccupied by the extent to which scientific uncertainty and debate will delay international agreements. For those that share their conviction that a climate agreement is needed urgently (I do not), please note that the largest anthropogenic contributor to global warming—fossil fuel emissions of $CO_2$—is fairly well understood. Thus, a climate agreement might start with this source and move on to other sources and gases as they become better quantified.

The authors' focus on greenhouse uncertainties reveals that what *is* urgently needed is serious scholarly attention to the comparative political, economic, and environmental aspects of the various accounting systems that have been proposed. Hammond's, Rodenburg's, and Moomaw's counterfactual claim that their index is ideal for diplomatic purposes is not sufficient.

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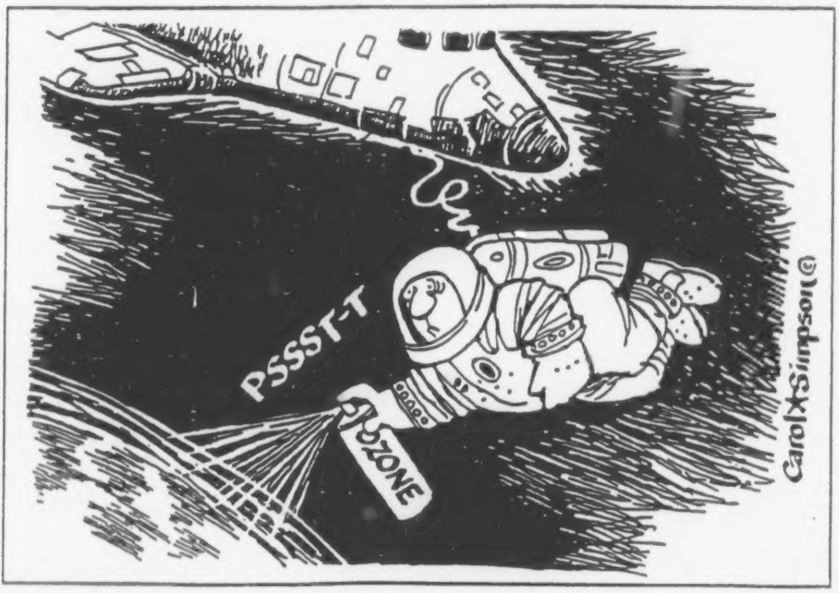

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1. D. G. Victor, "Calculating Greenhouse Budgets," *Nature* 347 (1990):431; and R. S. Eckaus, "Comparing the Effects of Greenhouse Gas Emissions on Global Warming," Working Paper no. 022WP (Cambridge, Mass.: Massachusetts Institute of Technology, Center for Energy Policy Research, 1990).

2. V. Smil, "Planetary Warming: Realities and Responses," *Population and Development Review* 16 (1990):1–29.

3. H. Schutz, A. Holzapfel-Pschorn, R. Conrad, H. Rennenberg, and W. Seiler, "A 3-Year Continuous Record on the Influence of Daytime, Season, and Fertilizer Treatment on Methane Emission Rates from an Italian Rice Paddy," *Journal of Geophysical Research* 94, no. D13 (1989):16405–416.

4. R. J. Cicerone and R. S. Oremland, "Biogeochemical Aspects of Atmospheric Methane," *Global Biogeochemical Cycles* 2, no. 4 (December 1988): 299–327.

IN LAST MONTH'S *Environment*, Allen Hammond, Eric Rodenburg, and William Moomaw point out the need for reliable indices to allocate relative responsibility for greenhouse emissions among countries so that international climate negotiations can proceed rationally. Such indices should be faithful to physical reality as well as simple, understandable, and flexible enough for use in negotiations and policymaking. The index the authors describe may meet the policy criterion, but, unfortunately, it does not meet the scientific one and, thus, would lead to undesirable decisions if applied in its present form.

They base their index on the "airborne fraction" for each gas, which is the ratio of the observed global atmospheric increase

*(continued on page 42)*

## Overview

*(continued from page 5)*

during a year to the estimated total emissions over the same period. There are a number of serious problems in this approach, but two stand out. First, because the atmospheric residence times of the relevant gases are much longer than one year, the amount removed each year by global sinks is only weakly related to the amount emitted that year and is mostly a function of the amount remaining in the atmosphere from previous years' emissions.[1] For example, about 98 percent of any year's emissions of $CO_2$ are still in the atmosphere at the end of that year.[2] For $CH_4$, 95 percent is still present.[3] In other words, even if all anthropogenic emissions were to stop suddenly, global sinks would still absorb more than 95 percent as much $CO_2$ next year as they would if emissions had continued. By using the airborne fraction, therefore, this index has the perverse characteristic that the more gases released in the past, the less any nation's responsibility is today because a larger atmospheric burden at the start of a year results in a larger amount removed that year.

Another characteristic of this index is that, because the global airborne fraction is used, each nation's responsibility depends on the past actions of all nations rather than on just its own actions. In reality, however, the amount of gas absorbed by sinks each year depends on the overall atmospheric burden, which has been contributed to unequally by different countries. The only way that the present global airborne fraction would be an appropriate indicator for each nation separately would be if each nation's share of the total historic emissions were equal to its share of emissions today. Of course, these conditions do not exist. By using a global average, the authors' index essentially shields countries that have emitted more in the past.

An alternative accounting system might match each nation's present emissions only with what is removed from its share of the overall burden because of the past emissions of that country alone (its "natural debt"[4]). Whether national or global values are used, however, the index has a further perverse characteristic: Because more greenhouse gases are added to the atmosphere each year than are removed, global concentrations and, consequently, the amounts removed by sinks are both increasing. For example, if $CH_4$ emissions were to increase at a steady annual rate of 1 percent, global concentrations would continue to rise by a greater amount each year, but the airborne fraction would fall from its present value of about 18 percent and the $CH_4$ index value would fall for about 20 years. Beyond that time, the index value would start to rise, but much more slowly than would the atmospheric burden. After some 50 years, the airborne fraction would be nearly constant at 8.6 percent, and after about 70 years, the index would be rising as fast as the atmospheric burden. Alternatively, if $CH_4$ emissions were to remain constant, the index would fall for about 60 years, even as atmospheric burden rose. If $CH_4$ emissions were suddenly to stop altogether, the airborne fraction would become negative infinity.[5] These characteristics make an index based on airborne fractions seem quite unreliable for comparisons from year to year, which is one of the most important uses for such indices.

The second problem with the authors' approach is that it does not, as they claim, avoid "adopting an arbitrary future time period" or, in apparent contradiction, focus on "the instantaneous change in radiative forcing." Unfortunately, it is not possible to avoid choosing a time horizon when dealing with greenhouse gases. Anytime one considers making tradeoffs among activities that have different time constants, such as those that emit greenhouse gases of different lifetimes, one either explicitly or implicitly chooses a time horizon (or discount rate). There is no way out, although there are many ways to avoid an explicit choice.

In their article in *Nature*,[6] the authors state that "the only logical time horizon, other than one year, is an infinite one." Yet most people are willing to spend resources to protect the future well beyond one year but are reluctant to sacrifice present needs for a distant future with unknown needs and capabilities. Because most observers favor intermediate time horizons on the order of 100 years, very short or very long time horizons seem illogical.[7] Thus, by using an instantaneous measure, the index tends to be biased against developing countries because they produce relatively more short-lived greenhouse gases, such as $CH_4$. Moreover, the index does not distinguish between long- and short-lived greenhouse gases.

The authors may be correct in their belief that attempts to agree on time horizons could delay international negotiations. This is no excuse, however, for succumbing to the wishes of some negotiators just to give them one number. To do so would result in policies based on a superficially simple index in which some arbitrary time horizon is buried (if well hidden). It would be like encouraging policymakers who deal with nuclear hazards to operate under the impression that all radioactive materials decay at the same rate. A better approach would be to insist on describing the sensitivities in such a way that the choice of a time horizon becomes part of the negotiations. Some things, including a time horizon, cannot be

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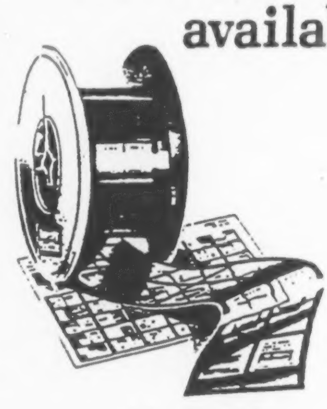

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### CORRECTION

The editorial in the January/February issue should have identified the United Nations Environment Programme as the organization that recently supported the diagnoses of water-resource problems in the Zambezi and Lake Chad basins. *Environment* regrets the error.

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sacrificed on the altar of simplicity without creating a significant distortion in the accounting system.

Most of these distortions (and others not mentioned here) act to increase the apparent responsibilities of developing countries as compared to those of developed countries. This distortion explains the authors' conclusion that developing countries "accounted for . . . a far larger proportion [of greenhouse-gas emissions] than generally has been recognized."

Developing an accurate, yet usable, index is a much more complex and difficult job than many people seem to think. Consequently, the attention given to this job has not been commensurate with its importance. There is no shame in making a proposal that, after more reflection based on peer review, is found to be inappropriate. In designing an index, however, it is important to specify exactly which policy questions are to be addressed because different indices are appropriate for different questions. There is no universal index appropriate for all issues related to global warming negotiations. Considerably more work and thought will be needed before scientifically valid, easily understandable, and yet politically acceptable indices are found.

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1. J. Firor, "Public Policy and the Airborne Fraction," *Climatic Change* (1988):103–05.
2. U. Seigenthaler, "Uptake of Excess $CO_2$ by an Outcropping Model of the Ocean," *Journal of Geophysical Research* 88 (1983):3599.
3. K. P. Shine, et al., "Radiative Forcing of Climate," *IPCC Scientific Assessment* (Cambridge, England: Cambridge University Press, 1990).
4. K. R. Smith, "Allocating Responsibility for Global Warming: The Natural Debt Index," *Ambio* 20 (1991), forthcoming.
5. Firor, note 1 above.
6. The index was first published in A. L. Hammond, E. Rodenburg, and W. R. Moomaw, "Accountability in the Greenhouse," *Nature* 347 (1990):705. Comparisons based on the index were presented earlier in World Resources Institute, United Nations Environment Programme, and United Nations Development Programme, *World Resources 1990–91* (New York and Oxford, England: Oxford University Press, 1990).
7. R. A. Rodhe, "Comparison of the Contribution of Various Gases to the Greenhouse Effect," *Science* 248 (1990):1217.

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THESE COMMENTARIES INCLUDE many constructive suggestions and valid comments. They also levy a number of charges that are incorrect or irrelevant. Perhaps the most serious charge is that our index method, compared to that developed by IPCC, acts "to increase the apparent responsibilities of developing countries" (according to Kirk Smith) and "holds the countries that produce greater quantities of the longer-lived gases, such as $CO_2$, less accountable than does a $CO_2$-equivalent index based on global warming potential" (according to Susan Subak). A useful way to determine the truth or falsity of these assertions is to compare the two methods carefully. Accordingly, we have applied the IPCC global warming potentials for three different time horizons to our emissions data; the results are summarized in Table 1 on this page. The equations used to calculate national contributions to greenhouse forcing appear in the box on page 44.

Except for the 500-year time horizon, the GWP approach yields higher contributions for developing and high-$CH_4$-emitting countries and lower contributions for industrialized and high-$CO_2$-emitting countries than does our GFC approach. Clearly, our Greenhouse Index displays no bias against developing countries in practice, and the assumptions on which such criticisms are based must be questioned. The calculation also demonstrates our point about the substantial variation in results obtained with the GWP approach, depending on the time horizon chosen.

We agree with David Victor that our index assigns accountability to current emitters. We regard it, however, as an advantage and not a disadvantage because it tends to emphasize the rate of forcing. It is the rate of climate change that will determine how severe the effects of climate change are on societies and ecosystems.[1] This point is also pertinent in regard to Subak's preference for a cumulative index. Both cumulative and current indices are potentially useful. We know that our index, applied retrospectively over a period of several decades, can show historical emissions.

Of course, any index can be improved, and we welcome suggestions for improvements. However, Subak is simply incorrect in asserting that we neglect to consider the atmospheric residence time of the different greenhouse gases. The airborne fraction is, in effect, a measure of those lifetimes, as we explained in the article. Indeed, as Ralph Cicerone suggests, our method is equivalent to the assumption of atmospheric residence times for CFCs, $CO_2$, and $CH_4$, respectively, of 100, 71, and 26 years for 1988 emissions, based on airborne fractions of 1, 0.71, and 0.26.

Smith and Victor attribute a number of supposed flaws in our index to the use of the airborne fraction. Clearly, it is an imprecise measure, but so are the model-based calculations of atmospheric lifetimes used in GWPs, which involve judgments about numerous uncertainties. The use of airborne fractions would break down in the extreme conditions that Smith hypothesizes, but those conditions bear little resemblance to the real world of the next decade or so. As Table 1 indicates, Smith's arguments about our approach's "perverse characteristic" that "shields countries that have emitted more in the past" do not appear to stand up in practice. As for being "faithful to physical reality," it is hard to describe the observed behavior of the Earth's atmosphere, which is the basis of the airborne fraction, as anything but real. Thus, the real criticism appears to be that the airborne fraction does not lend itself to a convenient theoretical formulation of its relationship to the present and past states of the atmosphere—a fact that we cheerfully admit. Actually, the weaknesses of the airborne fraction as a basis for an index are also its greatest strengths: It is simple and empirical, it gives reasonable results, and it avoids the awkward need to choose explicitly a theoretical framework or a time horizon.

We agree with Victor's comment that our method is, in principle, vulnerable to the natural variability of the biogeochemical cycles over time, but we do not think this is likely to be a significant problem. Given the state of knowledge of the Earth's system, any accounting formula will have to be recalibrated or adjusted periodically, as the ozone-depletion potentials used in the Montreal protocol negotiations have been.

TABLE 1

## DEVELOPED AND DEVELOPING COUNTRIES' CONTRIBUTIONS TO 1988 GREENHOUSE FORCING

| Index | Time horizon | Developed countries (percent) | Developing countries (percent) |
|---|---|---|---|
| GWP[a] | 20 years | 49.3 | 50.7 |
| GWP | 100 years | 52.3 | 47.7 |
| GWP | 500 years | 55.0 | 45.0 |
| GFC[b] | | 54.0 | 46.0 |

[a] The accounting system based on global warming potentials (GWPs) is favored by the Intergovernmental Panel on Climate Change.

[b] The authors' Greenhouse Index, based on greenhouse forcing contributions (GFCs), uses no explicit time horizon.

## GREENHOUSE INDEX EQUATIONS

The contribution of a given country to greenhouse forcing, or its index score (I), is calculated thus:

$$I = \sum_i e_i GFC_i = \sum_i e_i r_i Af_i$$

or, alternatively,

$$I = \sum_i e_i GWP_i$$

where $\sum_i$ means to sum over all gases ($i$)

$e_i$ = the country's emissions of gas $i$
$GFC_i$ = the greenhouse forcing contribution of gas $i$
$r_i$ = the radiative forcing of gas $i$
$Af_i$ = the airborne fraction of gas $i$ $= \dfrac{\text{the net atmospheric increase of gas } i}{\text{the total global emissions of gas } i}$

$$GWP_i = \frac{\int_0^N r_i c_i dt}{\int_0^N r_c c_c dt}$$

$c_i$ = the atmospheric concentration of gas $i$
$r_c$ = the radiative forcing of carbon dioxide
$c_c$ = the atmospheric concentration of carbon dioxide
$N$ = the integration period (or time horizon)

As to emissions, which, as Cicerone points out, are ultimately more important than accounting schemes, we agree with Subak that our assessment could be made more comprehensive when adequate information on more sources and other greenhouse gases becomes available. However, it is not now available, to our knowledge, although we await with interest the publication of Subak's data on nitrous oxide emissions. Generalization to include aerosols and indirect effects would also improve the treatment, as Cicerone suggests.

Cicerone questions our methane data. We have rechecked with our source, and they have revised downward the earlier estimate of atmospheric methane that they had provided to us.[2] Thus, we now agree with Cicerone's figure for the increase in atmospheric methane. Regarding total emissions, we built our estimates from the bottom up, based on emissions from sources explicitly attributable to specific countries, rather than by allocating global emissions. For that reason, our estimates of anthropogenic $CH_4$ emissions do not include the effects of biomass burning (we do not know of any reliable estimates of these emissions listed by country), which may account for the difference between our total figure and Cicerone's.

We entirely agree with Cicerone that there is a need for futher research on anthropogenic emissions and on natural flows of greenhouse gases. Indeed, we are acutely aware of the uncertainties in many of our estimates and of the narrowness of the scientific base for the assumptions on which they rest, and we welcome better data and continue to update our emission estimates as better information becomes available. However, it has been our experience that even a major change in the assumptions underlying a single source of emissions does not significantly alter country rankings, if at all.

We continue to believe that our index is a useful measure of greenhouse-gas emissions, as are, for many purposes, GWP-based indices. We acknowledge that international agreements may ultimately require several different measures, as Subak, Cicerone, Smith, and Victor suggest. Our purpose in assembling the emission data base and in developing the index was descriptive, not prescriptive. How an international climate convention should treat different sources of greenhouse gases or assign national obligations is not at all obvious, at least not to us. Negotiations should at least start with a clear view of the problem as it really is—the distribution of emissions by source, by country, and per person. We believe our work has been useful to that end.

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*Tufts University*
*Medford, Massachusetts*

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1. M. D. Handel, letter to *Nature* (forthcoming).
2. M. A. K. Khalil, personal communication with the authors.

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# SCIENTIFIC ASSESSMENT
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World Meteorological Organization/United Nations Environment Programme

# PREFACE

The Intergovernmental Panel on Climate Change (IPCC) was jointly established by our two organizations in 1988. Under the chairmanship of Professor Bert Bolin, the Panel was charged with:

(i) assessing the scientific information that is related to the various components of the climate change issue, such as emissions of major greenhouse gases and modification of the Earth's radiation balance resulting therefrom, and that needed to enable the environmental and socio-economic consequences of climate change to be evaluated, and

(ii) formulating realistic response strategies for the management of the climate change issue.

The Panel began its task by establishing Working Groups I, II and III respectively to:

(a) assess available scientific information on climate change,

(b) assess environmental and socio-economic impacts of climate change, and

(c) formulate response strategies.

It also established a Special Committee on the Participation of Developing Countries to promote, as quickly as possible, the full participation of developing countries in its activities.

This Policymakers' Summary of Working Group I should be read in conjunction with the rest of the IPCC first assessment report; the latter consists of the reports and policymakers' summaries of the three Working Groups and the Special Committee, and the IPCC overview and conclusions.

The Chairman of Working Group I, Dr John Houghton, and his Secretariat, have succeeded beyond measure in mobilizing the co-operation and enthusiasm of hundreds of scientists from all over the world. Their main report is of remarkable depth and breadth, and this Policymakers' Summary translates these complex scientific issues into language which is understandable to the non-specialist. We take this opportunity to congratulate and thank the Chairman for a job well done.

**G.O.P. Obasi**
*Secretary-General*
*World Meteorological Organization*

**M.K. Tolba**
*Executive Director*
*United Nations Environment Programme*

*July 1990*

# FOREWORD

Many previous reports have addressed the question of climate change which might arise as a result of man's activities. In preparing the IPCC Scientific Assessment*, Working Group I has built on these, taking into account significant work undertaken and published since then. Particular attention is paid to what is known regarding the detail of climate change on a regional level.

In the preparation of the main Assessment most of the active scientists working in the field have been involved. One hundred and seventy scientists from 25 countries have contributed to it, either through participation in the twelve international workshops organized specially for the purpose or through written contributions. A further 200 scientists have been involved in the peer review of the draft report. This has helped to ensure a high degree of consensus amongst authors and reviewers regarding the results presented although, as in any developing scientific topic, there is a minority of views that are outside this consensus and which we have not been able to accommodate. The Policymakers' Summary was subject to a similar, wide, peer review, and the text was agreed at the final meeting of Working Group I in May 1990. They are therefore authoritative statements of the views of the international scientific community at this time.

It gives me pleasure to acknowledge the contributions of so many, in particular the Lead Authors, who have given freely of their expertise and time in the preparation of this report, and the modelling centres who have readily provided results. I would also like to thank the core team at the Meteorological Office, Bracknell, who were responsible for organizing most of the workshops and preparing the report, and the Departments of Environment and Energy in the United Kingdom who provided the necessary financial support.

I am confident that the Assessment and its Summary will provide the necessary firm scientific foundation for the forthcoming discussions and negotiations on the appropriate strategy for response and action regarding the issue of climate change. It is thus, I believe, a significant step forward in meeting what is potentially the greatest global environmental challenge facing mankind.

**John Houghton**
*Chairman, IPCC Working Group I*

*Meteorological Office*
*Bracknell*
*United Kingdom*

*July 1990*

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*Scientific Assessment of Climate Change, WMO/UNEP Intergovernmental Panel on Climate Change; Geneva (1990). Also published as: Climate Change: The IPCC Scientific Assessment; Houghton, J.T., G.J. Jenkins and J.J. Ephraums (Editors), Cambridge University Press, Cambridge, 1990.

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# EXECUTIVE SUMMARY

## We are certain of the following:

- there is a natural greenhouse effect which already keeps the Earth warmer than it would otherwise be.
- emissions resulting from human activities are substantially increasing the atmospheric concentrations of the greenhouse gases: carbon dioxide, methane, chlorofluorocarbons (CFCs) and nitrous oxide. These increases will enhance the greenhouse effect, resulting on average in an additional warming of the Earth's surface. The main greenhouse gas, water vapour, will increase in response to global warming and further enhance it.

## We calculate with confidence that:

- some gases are potentially more effective than others at changing climate, and their relative effectiveness can be estimated. Carbon dioxide has been responsible for over half the enhanced greenhouse effect in the past, and is likely to remain so in the future.
- atmospheric concentrations of the long-lived gases (carbon dioxide, nitrous oxide and the CFCs) adjust only slowly to changes in emissions. Continued emissions of these gases at present rates would commit us to increased concentrations for centuries ahead. The longer emissions continue to increase at present-day rates, the greater reductions would have to be for concentrations to stabilize at a given level.
- the long-lived gases would require immediate reductions in emissions from human activities of over 60% to stabilize their concentrations at today's levels; methane would require a 15–20% reduction.

## Based on current model results, we predict:

- under the IPCC Business-as-Usual (Scenario A) emissions of greenhouse gases, a rate of increase of global mean temperature during the next century of about 0.3°C per decade (with an uncertainty range of 0.2°C to 0.5°C per decade); this is greater than that seen over the past 10,000 years. This will result in a likely increase in global mean temperature of about 1°C above the present value by 2025 and 3°C before the end of the next century. The rise will not be steady because of the influence of other factors.
- under the other IPCC emission scenarios which assume progressively increasing levels of controls, rates of increase in global mean temperature of about 0.2°C per decade (Scenario B), just above 0.1°C per decade (Scenario C) and about 0.1°C per decade (Scenario D).
- that land surfaces warm more rapidly than the ocean, and high northern latitudes warm more than the global mean in winter.
- regional climate changes different from the global mean, although our confidence in the prediction of the detail of regional changes is low. For example, temperature increases in southern Europe and central North America are predicted to be higher than the global mean, accompanied on average by reduced summer precipitation and soil moisture. There are less consistent predictions for the tropics and the southern hemisphere.
- under the IPCC Business-as-Usual emissions scenario, an average rate of global mean sea level rise of about 6cm per decade over the next century (with an uncertainty range of 3–10cm per decade), mainly due to thermal expansion of the oceans and the melting of some land ice. The predicted rise is about 20cm in global mean sea level by 2030, and 65cm by the end of the next century. There will be significant regional variations.

**There are many uncertainties in our predictions particularly with regard to the timing, magnitude and regional patterns of climate change, due to our incomplete understanding of:**

- sources and sinks of greenhouse gases, which affect predictions of future concentrations
- clouds, which strongly influence the magnitude of climate change
- oceans, which influence the timing and patterns of climate change
- polar ice sheets which affect predictions of sea level rise

These processes are already partially understood, and we are confident that the uncertainties can be reduced by further research. However, the complexity of the system means that we cannot rule out surprises.

## Our judgement is that:

- Global mean surface air temperature has increased by 0.3°C to 0.6°C over the last 100 years, with the five global mean warmest years being in the 1980s. Over the same period global sea level has increased by 10–20 cm. These increases have not been smooth with time, nor uniform over the globe.
- The size of this warming is broadly consistent with predictions of climate models, but it is also of the same magnitude as natural climate variability. Thus the observed increase could be largely due to this natural variability; alternatively this variability and other human factors could have offset a still larger human-induced greenhouse warming. The unequivocal detection of the enhanced greenhouse effect from observations is not likely for a decade or more.
- There is no firm evidence that climate has become more variable over the last few decades. However, with an increase in the mean temperature, episodes of high temperatures will most likely become more frequent in the future, and cold episodes less frequent.
- Ecosystems affect climate, and will be affected by a changing climate and by increasing carbon dioxide concentrations. Rapid changes in climate will change the composition of ecosystems; some species will benefit while others will be unable to migrate or adapt fast enough and may become extinct. Enhanced levels of carbon dioxide may increase productivity and efficiency of water use by vegetation. The effect of warming on biological processes, although poorly understood, may increase the atmospheric concentrations of natural greenhouse gases.

## To improve our predictive capability, we need:

- to **understand** better the various climate-related processes, particularly those associated with clouds, oceans and the carbon cycle
- to **improve** the systematic observation of climate-related variables on a global basis, and further investigate changes which took place in the past
- to **develop** improved models of the Earth's climate system
- to **increase** support for national and international climate research activities, especially in developing countries
- to **facilitate** international exchange of climate data

## Introduction: what is the issue?

There is concern that human activities may be inadvertently changing the climate of the globe through the enhanced greenhouse effect, by past and continuing emissions of carbon dioxide and other gases which will cause the temperature of the Earth's surface to increase — popularly termed the "global warming". If this occurs, consequent changes may have a significant impact on society.

The purpose of the Working Group I report, as determined by the first meeting of IPCC, is to provide a scientific assessment of:

1) the factors which may affect climate change during the next century especially those which are due to human activity.
2) the responses of the atmosphere–ocean–land-ice system.
3) current capabilities of modelling global and regional climate changes and their predictability.
4) the past climate record and presently observed climate anomalies.

On the basis of this assessment, the report presents current knowledge regarding predictions of climate change (including sea level rise and the effects on ecosystems) over the next century, the timing of changes together with an assessment of the uncertainties associated with these predictions.

This Policymakers' Summary aims to bring out those elements of the main report which have the greatest relevance to policy formulation, in answering the following questions:

- What factors determine global climate?
- What are the greenhouse gases, and how and why are they increasing?
- Which gases are the most important?
- How much do we expect the climate to change?
- How much confidence do we have in our predictions?
- Will the climate of the future be very different?
- Have human activities already begun to change global climate?
- How much will the sea level rise?
- What will be the effects on ecosystems?
- What should be done to reduce uncertainties, and how long will this take?

This report is intended to respond to the practical needs of the policymaker. It is neither an academic review, nor a plan for a new research programme. Uncertainties attach to almost every aspect of the issue, yet policymakers are looking for clear guidance from scientists; **hence authors have been asked to provide their best-estimates wherever possible**, together with an assessment of the uncertainties.

This report is a summary of our understanding in 1990. Although continuing research will deepen this understanding and require the report to be updated at frequent intervals, basic conclusions concerning the reality of the enhanced greenhouse effect and its potential to alter global climate are unlikely to change significantly. Nevertheless, the complexity of the system may give rise to surprises.

## What factors determine global climate?

There are many factors, both of natural and human origin, that determine the climate of the Earth. We look first at those which are natural, and then see how human activities might contribute.

## What natural factors are important?

The driving energy for weather and climate comes from the Sun. The Earth intercepts solar radiation (including that in the short-wave, visible, part of the spectrum); about a third of it is reflected, the rest is absorbed by the different components (atmosphere, ocean, ice, land and biota) of the climate system. The energy absorbed from solar radiation is balanced (in the long term) by outgoing radiation from the Earth and atmosphere; this terrestrial radiation takes the form of long-wave invisible infra-red energy, and its magnitude is determined by the temperature of the Earth–atmosphere system.

There are several natural factors which can change the balance between the energy absorbed by the Earth and that emitted by it in the form of long-wave infra-red radiation; these factors cause the **radiative forcing** on climate. The most obvious of these is a change in the output of energy from the Sun. There is direct evidence of such variability over the 11-year solar cycle, and longer-period changes may also occur. Slow variations in the Earth's orbit affect the seasonal and latitudinal distribution of solar radiation; these were probably responsible for initiating the ice ages.

One of the most important factors is the **greenhouse effect**; a simplified explanation of which is as follows. Short-wave solar radiation can pass through the clear atmosphere relatively unimpeded. But long-wave terrestrial radiation emitted by the warm surface of the Earth is partially absorbed and then re-emitted by a number of trace gases in the cooler atmosphere above. Since, on average, the outgoing long-wave radiation balances the incoming solar radiation, both the atmosphere and the surface will be warmer than they would be without the greenhouse gases.

The main natural greenhouse gases are not the major constituents, nitrogen and oxygen, but water vapour (the biggest contributor), carbon dioxide, methane, nitrous oxide, and ozone in the troposphere (the lowest 10–15km of the atmosphere) and stratosphere.

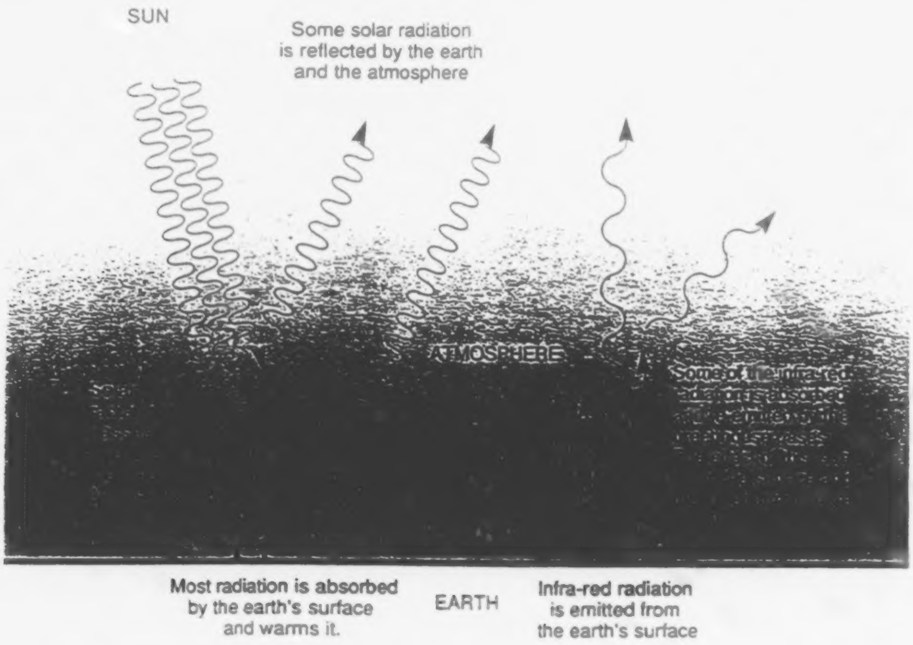
**Aerosols** (small particles) in the atmosphere can also affect climate because they can reflect and absorb radiation. The most important natural perturbations result from explosive volcanic eruptions which affect concentrations in the lower stratosphere. Lastly, the climate has its own **natural variability** on all time-scales and changes occur without any external influence.

## How do we know that the natural greenhouse effect is real?

The greenhouse effect is real; it is a well understood effect, based on established scientific principles. We know that the greenhouse effect works in practice, for several reasons.

Firstly, the mean temperature of the Earth's surface is already warmer by about 33°C (assuming the same reflectivity of the earth) than it would be if the natural greenhouse gases were not present. Satellite observations of the radiation emitted from the Earth's surface and through the atmosphere demonstrate the effect of the greenhouse gases.

Secondly, we know the composition of the atmospheres of Venus, Earth and Mars are very different, and their surface temperatures are in general agreement with greenhouse theory. Thirdly, measurements from ice cores going back 160,000 years show that the Earth's temperature closely paralleled the amount of carbon dioxide and methane in the atmosphere. Although we do not know the details of cause and effect, calculations indicate that changes in these greenhouse gases


SUN
Some solar radiation is reflected by the earth and the atmosphere
ATMOSPHERE
Some of the infra-red
Most radiation is absorbed by the earth's surface and warms it.
EARTH
Infra-red radiation is emitted from the earth's surface

A simplified diagram illustrating the greenhouse effect.

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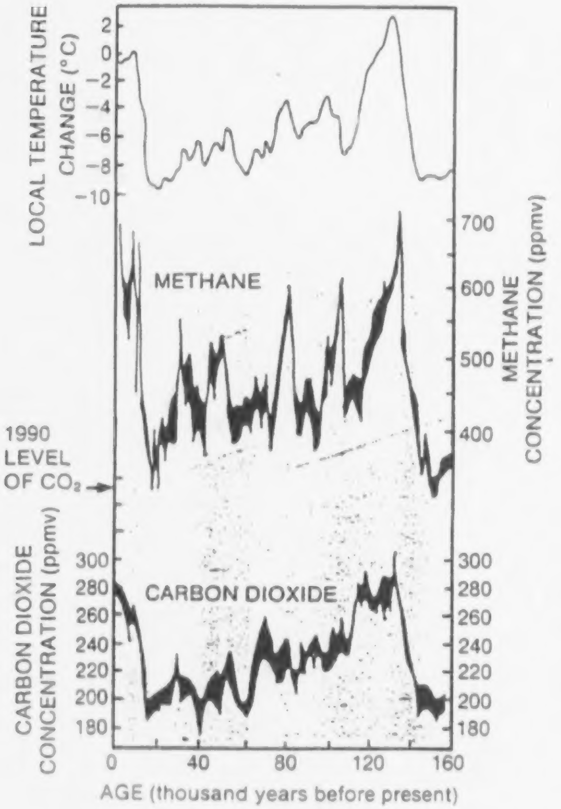

**Analysis of air trapped in Antarctic ice cores shows that methane and carbon dioxide concentrations were closely correlated with the local temperature over the last 160,000 years. Present-day concentrations of carbon dioxide are indicated.**

were part, but not all, of the reason for the large (5–7 °C) global temperature swings between ice ages and interglacial periods.

## How might human activities change global climate?

Naturally occurring greenhouse gases keep the Earth warm enough to be habitable. By increasing their concentrations, and by adding new greenhouse gases like chlorofluorocarbons (CFCs), humankind is capable of raising the global-average annual-mean surface-air temperature (which, for simplicity, is referred to as the "global temperature"), although we are uncertain about the rate at which this will occur. Strictly, this is an **enhanced** greenhouse effect – above that occurring due to natural greenhouse gas concentrations; the word "enhanced" is usually omitted, but it should not be forgotten. Other changes in climate are expected to result, for example changes in precipitation, and a global warming will cause sea levels to rise; these are discussed in more detail later.

There are other human activities which have the potential to affect climate. A change in the albedo (reflectivity) of the land, brought about by **desertification or deforestation** affects the amount of solar energy absorbed at the Earth's surface. Human-made **aerosols**, from sulphur emitted largely in fossil fuel combustion, can modify clouds and this may act to lower temperatures. Lastly, changes in **ozone in the stratosphere** due to CFCs may also influence climate.

## What are the greenhouse gases and why are they increasing?

We are certain that the concentrations of greenhouse gases in the atmosphere have changed naturally on ice-age time-scales, and have been increasing since pre-industrial times due to human activities. The table opposite summarizes the present and pre-industrial abundances, current rates of change and present atmospheric lifetimes of greenhouse gases influenced by human activities. Carbon dioxide, methane, and nitrous oxide all have significant natural and human sources, while the CFCs are only produced industrially.

Two important greenhouse gases, water vapour and ozone, are not included in the table opposite. Water vapour has the largest greenhouse effect, but its concentration in the troposphere is determined internally within the climate system, and, on a global scale, is not affected by human sources and sinks. Water vapour will increase in response to global warming and further enhance it; this process is included in climate models. The concentration of ozone is changing both in the stratosphere and the troposphere due to human activities, but it is difficult to quantify the changes from present observations.

For a thousand years prior to the industrial revolution, abundances of the greenhouse gases were relatively constant. However, as the world's population increased, as the world became more industrialized and as agriculture developed, the abundances of the greenhouse gases increased markedly. The figures on page 9 illustrate this for carbon dioxide, methane, nitrous oxide and CFC-11.

Since the industrial revolution the combustion of fossil fuels and deforestation have led to an increase of 26% in carbon dioxide concentration in the atmosphere. We know the magnitude of the present day fossil-fuel source, but the input from deforestation cannot be estimated accurately. In addition, although about half of the emitted carbon

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## SUMMARY OF KEY GREENHOUSE GASES AFFECTED BY HUMAN ACTIVITIES

| | Carbon Dioxide | Methane | CFC-11 | CFC-12 | Nitrous Oxide |
|---|---|---|---|---|---|
| Atmospheric concentration | ppmv | ppmv | pptv | pptv | ppbv |
| Pre-industrial (1750–1800) | 280 | 0.8 | 0 | 0 | 288 |
| Present day (1990) | 353 | 1.72 | 280 | 484 | 310 |
| Current rate of change per year | 1.8<br>(0.5%) | 0.015<br>(0.9%) | 9.5<br>(4%) | 17<br>(4%) | 0.8<br>(0.25%) |
| Atmospheric lifetime (years) | (50–200)* | 10 | 65 | 130 | 150 |

ppmv=parts per million by volume;
ppbv=parts per billion (thousand million) by volume;
pptv=parts per trillion (million million) by volume.
*The way in which $CO_2$ is absorbed by the oceans and biosphere is not simple and a single value cannot be given; refer to the main report for further discussion.

dioxide stays in the atmosphere, we do not know well how much of the remainder is absorbed by the oceans and how much by terrestrial biota. Emissions of chlorofluorocarbons, used as aerosol propellants, solvents, refrigerants and foam-blowing agents, are also well known; they were not present in the atmosphere before their invention in the 1930s.

The sources of methane and nitrous oxide are less well known. Methane concentrations have more than doubled because of rice production, cattle rearing, biomass burning, coal mining and venting of natural gas; also, fossil fuel combustion may have also contributed through chemical reactions in the atmosphere which reduce the rate of removal of methane. Nitrous oxide has increased by about 8% since pre-industrial times, presumably due to human activities; we are unable to specify the sources, but it is likely that agriculture plays a part.

The effect of ozone on climate is strongest in the upper troposphere and lower stratosphere. Model calculations indicate that ozone in the upper troposphere should have increased due to human-made emissions of nitrogen oxides, hydrocarbons and carbon monoxide. While at ground level, ozone has increased in the northern hemisphere in response to these emissions, observations are insufficient to confirm the expected increase in the upper troposphere. The lack of adequate observations prevents us from accurately quantifying the climatic effect of changes in tropospheric ozone.

In the lower stratosphere at high southern latitudes, ozone has decreased considerably due to the effects of CFCs, and there are indications of a global-scale decrease which, while not understood, may also be due to CFCs. These observed decreases should act to cool the Earth's surface, thus providing a small offset to the predicted warming produced by the other greenhouse gases. Further reductions in lower stratospheric ozone are possible during the next few decades as the atmospheric abundances of CFCs continue to increase.

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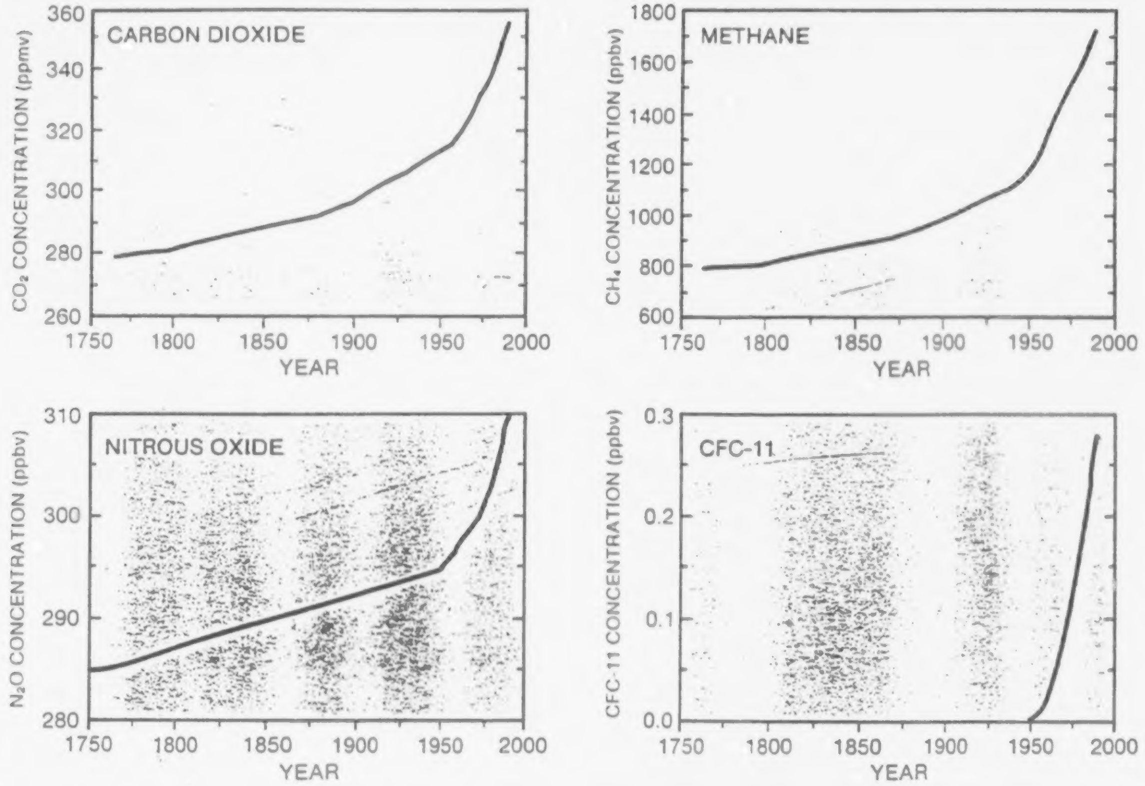

**Concentrations of carbon dioxide and methane after remaining relatively constant up to the 18th century, have risen sharply since then due to man's activities. Concentrations of nitrous oxide have increased since the mid-18th century, especially in the last few decades. CFCs were not present in the atmosphere before the 1930s.**

## Concentrations, lifetimes and stabilization of the gases

In order to calculate the atmospheric concentrations of carbon dioxide which will result from human-made emissions we use computer models which incorporate details of the emissions and which include representations of the transfer of carbon dioxide between the atmosphere, oceans and terrestrial biosphere. For the other greenhouse gases, models which incorporate the effects of chemical reactions in the atmosphere are employed.

The atmospheric lifetimes of the gases are determined by their sources and sinks in the oceans, atmosphere and biosphere. Carbon dioxide, chlorofluorocarbons and nitrous oxide are removed only slowly from the atmosphere and hence, following a change in emissions, their atmospheric concentrations take decades to centuries to adjust fully. Even if all human-made emissions of carbon dioxide were halted in the year 1990, about half of the increase in carbon dioxide concentration caused by human activities would still be evident by the year 2100.

In contrast, some of the CFC substitutes and methane have relatively short atmospheric lifetimes so that their atmospheric concentrations respond fully to emission changes within a few decades.

To illustrate the emission–concentration relationship clearly, the effect of hypothetical changes in carbon dioxide fossil fuel emissions is shown on page 10, (a) continuing global emissions at 1990 levels; (b) halving of emissions in 1990; (c) reductions in emissions of 2% per year (p.a.) from 1990 and (d) a 2% p.a. increase from 1990–2010 followed by a 2% p.a. decrease from 2010.

Continuation of present-day emissions are committing us to increased future concentrations, and the longer emissions continue to increase, the greater would reductions have to be to stabilize at a given level. If there are critical concentration levels that should not be exceeded, then the earlier emission reductions are made the more effective they are.

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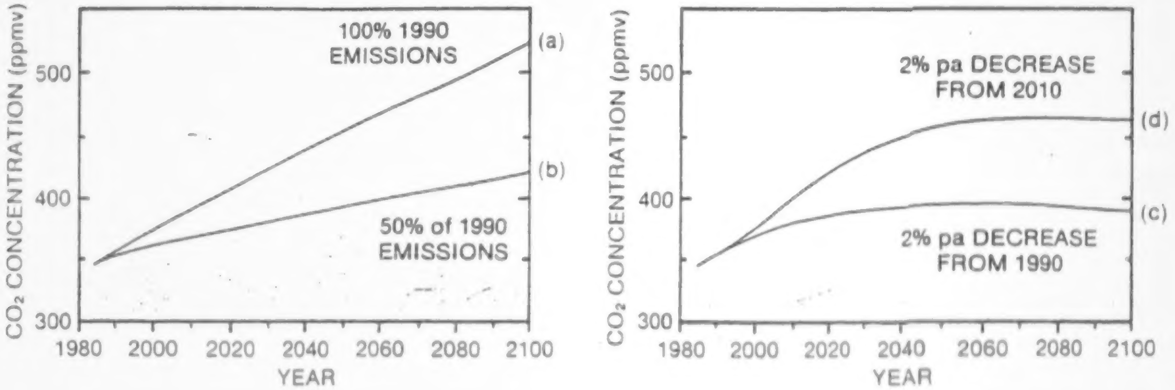

**The relationship between hypothetical fossil fuel emissions of carbon dioxide and its concentration in the atmosphere is shown in the case where (a) emissions continue at 1990 levels, (b) emissions are reduced by 50% in 1990 and continue at that level, (c) emissions are reduced by 2% p.a. from 1990, and (d) emissions, after increasing by 2% p.a. until 2010, are then reduced by 2% p.a. thereafter.**

The term "**atmospheric stabilization**" is often used to describe the limiting of the concentration of the greenhouse gases at a certain level. The amount by which human-made emissions of a greenhouse gas must be reduced in order to stabilize at present-day concentrations, for example, is shown in the box below. For most gases the reductions would have to be substantial.

## How will greenhouse gas abundances change in the future?

We need to know future greenhouse gas concentrations in order to estimate future climate change. As already mentioned, these concentrations depend upon the magnitude of human-made emissions and on how changes in climate and other environmental conditions may influence the biospheric processes that control the exchange of natural greenhouse gases, including carbon dioxide and methane, between the atmosphere, oceans and terrestrial biosphere — the greenhouse gas "feedbacks".

Four scenarios of future human-made emissions were developed by Working Group III. The first of these assumes that few or no steps are taken to limit greenhouse gas emissions, and this is therefore termed Business-as-Usual (BaU). (It should be noted that an aggregation of national forecasts of emissions of carbon dioxide and methane to the year 2025 undertaken by Working Group III resulted in global emissions 10–20% higher than in the BaU scenario.) The other three scenarios assume that progressively increasing levels of controls reduce the growth of

## STABILIZATION OF ATMOSPHERIC CONCENTRATIONS

Reductions in the human-made emissions of greenhouse gases required to stabilize concentrations at present-day levels:

| | |
|---|---|
| Carbon Dioxide | <60% |
| Methane | 15–20% |
| Nitrous Oxide | 70–80% |
| CFC-11 | 70–75% |
| CFC-12 | 75–85% |
| HCFC-22 | 40–50% |

Note that the stabilization of each of these gases would have different effects on climate, as explained in the next section.

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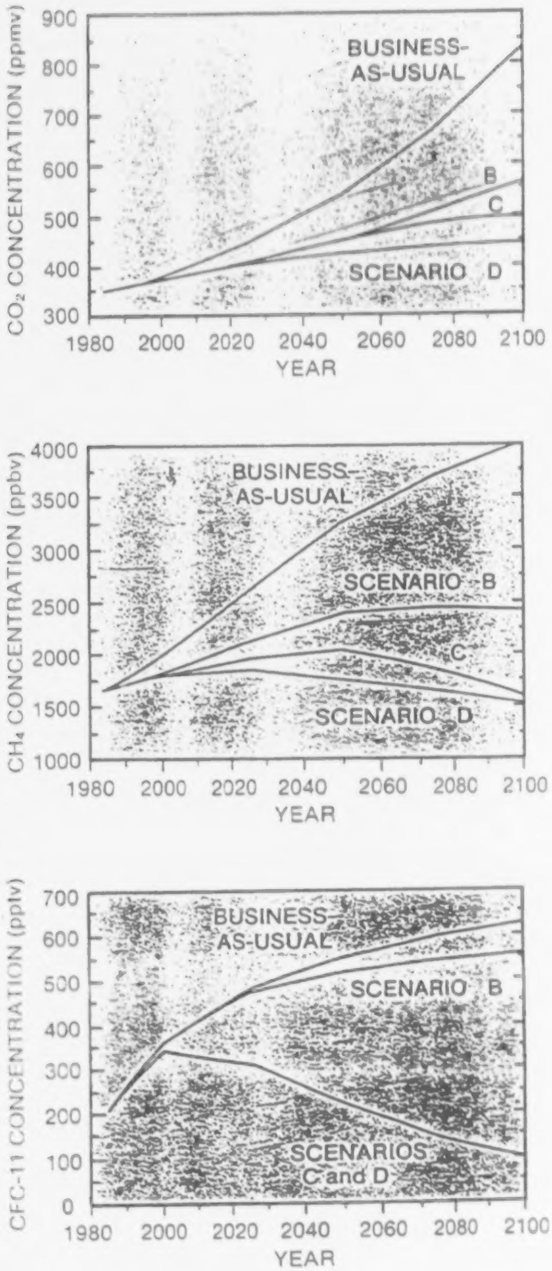
emissions; these are referred to as scenarios B, C, and D. They are briefly described in the Annex. Future concentrations of some of the greenhouse gases which would arise from these emissions are shown below.



**Atmospheric concentrations of carbon dioxide, methane and CFC-11 resulting from the four IPCC emissions scenarios.**

## Greenhouse gas feedbacks

Some of the possible feedbacks which could significantly modify future greenhouse gas concentrations in a warmer world are discussed in the following paragraphs.

The net emissions of carbon dioxide from terrestrial ecosystems will be elevated if higher temperatures increase respiration at a faster rate than photosynthesis, or if plant populations, particularly large forests, cannot adjust rapidly enough to changes in climate.

A net flux of carbon dioxide to the atmosphere may be particularly evident in warmer conditions in tundra and boreal regions where there are large stores of carbon. The opposite is true if higher abundances of carbon dioxide in the atmosphere enhance the productivity of natural ecosystems, or if there is an increase in soil moisture which can be expected to stimulate plant growth in dry ecosystems and to increase the storage of carbon in tundra peat. The extent to which ecosystems can sequester increasing atmospheric carbon dioxide remains to be quantified.

If the oceans become warmer, their net uptake of carbon dioxide may decrease because of changes in (i) the chemistry of carbon dioxide in sea-water, (ii) biological activity in surface waters, and (iii) the rate of exchange of carbon dioxide between the surface layers and the deep ocean. This last depends upon the rate of formation of deep water in the ocean which, in the North Atlantic for example, might decrease if the salinity decreases as a result of a change in climate.

Methane emissions from natural wetlands and rice paddies are particularly sensitive to temperature and soil moisture. Emissions are significantly larger at higher temperatures and with increased soil moisture; conversely, a decrease in soil moisture would result in smaller emissions. Higher temperatures could increase the emissions of methane at high northern latitudes from decomposable organic matter trapped in permafrost and methane hydrates.

As illustrated earlier, ice-core records show that methane and carbon dioxide concentrations changed in a similar sense to temperature between ice ages and interglacials.

Although many of these feedback processes are poorly understood, it seems likely that, overall, they will act to increase, rather than decrease, greenhouse gas concentrations in a warmer world.

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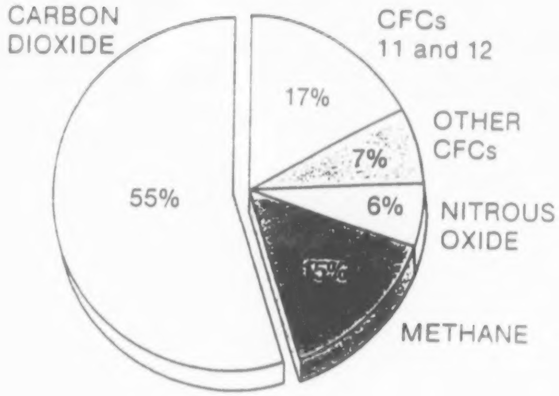
## Which gases are the most important?

We are certain that increased greenhouse gas concentrations increase radiative forcing. We can calculate the forcing with much more confidence than the climate change that results because the former avoids the need to evaluate a number of poorly understood atmospheric responses. We then have a base from which to calculate the relative effect on climate of an increase in **concentration** of each gas in the present-day atmosphere, both in absolute terms and relative to carbon dioxide. These relative effects span a wide range; methane is about 21 times more effective, molecule-for-molecule, than carbon dioxide, and CFC-11 about 12,000 times more effective. On a kilogram-per-kilogram basis, the equivalent values are 58 for methane and about 4,000 for CFC-11, both relative to carbon dioxide. Values for other greenhouse gases are to be found in the full report.

The total radiative forcing at any time is the sum of those from the individual greenhouse gases. We show in the figure below how this quantity has changed in the past (based on observations of greenhouse gases) and how it might change in the future (based on the four IPCC emissions scenarios). For simplicity, we can express total forcing in terms of the amount of carbon dioxide which would give that forcing; this is termed the **equivalent carbon dioxide concentration**. Greenhouse gases have increased since pre-industrial times (the mid-18th century) by an amount that is radiatively equivalent to about a 50% increase in carbon dioxide, although carbon dioxide itself has risen by only 26%; other gases have made up the rest.

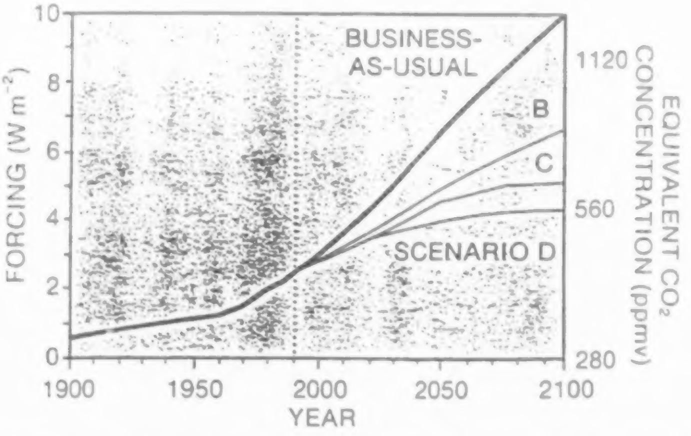


The contribution from each of the human-made greenhouse gases to the change in radiative forcing from 1980 to 1990. The contribution from ozone may also be significant, but cannot be quantified at present.

The contributions of the various gases to the total increase in climate forcing during the 1980s is shown above as a pie diagram; carbon dioxide is responsible for about half the decadal increase. (Ozone, the effects of which may be significant, is not included.)

## How can we evaluate the effect of different greenhouse gases?

To evaluate possible policy options, it is useful to know the relative radiative effect (and, hence, potential climate effect) of equal emissions of each of the greenhouse gases. The concept of relative **Global Warming Potentials (GWP)** has been developed to take into account the differing times that gases remain in the atmosphere.



Increase in radiative forcing since the mid-18th century, and predicted to result from the four IPCC emissions scenarios, also expressed as equivalent carbon dioxide concentrations.

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## GLOBAL WARMING POTENTIALS

The warming effect of an emission of 1 kg of each gas relative to that of carbon dioxide. These figures are best estimates calculated on the basis of the present-day atmospheric composition

| | Time Horizon | | |
|---|---|---|---|
| | 20 yr | 100 yr | 500 yr |
| Carbon dioxide | 1 | 1 | 1 |
| Methane (including indirect) | 63 | 21 | 9 |
| Nitrous oxide | 270 | 290 | 190 |
| CFC-11 | 4500 | 3500 | 1500 |
| CFC-12 | 7100 | 7300 | 4500 |
| HCFC-22 | 4100 | 1500 | 510 |

Global Warming Potentials for a range of CFCs and potential replacements are given in the full text

This index defines the time-integrated warming effect due to an instantaneous release of unit mass (1 kg) of a given greenhouse gas in today's atmosphere, relative to that of carbon dioxide. The relative importances will change in the future as atmospheric composition changes because, although radiative forcing increases in direct proportion to the concentration of CFCs, changes in the other greenhouse gases (particularly carbon dioxide) have an effect on forcing which is much less than proportional.

The GWPs in the table above are shown for three time-horizons, reflecting the need to consider the cumulative effects on climate over various time-scales. The longer time-horizon is appropriate for the cumulative effect; the shorter time-scale will indicate the response to emission changes in the short term. There are a number of practical difficulties in devising and calculating the values of the GWPs, and the values given here should be considered as preliminary. In addition to these direct effects, there are indirect effects of human-made emissions arising from chemical reactions between the various constituents. The indirect effects on stratospheric water vapour, carbon dioxide and tropospheric ozone have been included in these estimates.

## THE RELATIVE CUMULATIVE CLIMATE EFFECT OF 1990 MAN-MADE EMISSIONS

| | GWP (100 yr horizon) | 1990 emissions (Tg) | Relative contribution over 100 yr |
|---|---|---|---|
| Carbon dioxide | 1 | 26000† | 61% |
| Methane* | 21 | 300 | 15% |
| Nitrous oxide | 290 | 6 | 4% |
| CFCs | Various | 0.9 | 11% |
| HCFC-22 | 1500 | 0.1 | 0.5% |
| Others* | Various | | 8.5% |

*These values include the indirect effect of these emissions on other greenhouse gases via chemical reactions in the atmosphere. Such estimates are highly model dependent and should be considered preliminary and subject to change. The estimated effect of ozone is included under "others". The gases included under "others" are given in the full report.

†26000 Tg (teragrams) of carbon dioxide = 7 000 Tg (=7 Gt) of carbon

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### CHARACTERISTICS OF THE GREENHOUSE GASES

| GAS | MAJOR CONTRIBUTOR? | LONG LIFETIME? | SOURCE KNOWN? |
|---|---|---|---|
| Carbon dioxide | yes | yes | yes |
| Methane | yes | no | semi-quantitatively |
| Nitrous oxide | not at present | yes | qualitatively |
| CFCs | yes | yes | yes |
| HCFCs etc. | not at present | mainly no | yes |
| Ozone | possibly | no | qualitatively |

The table indicates, for example, that the effectiveness of methane in influencing climate will be greater in the first few decades after release, whereas emission of the longer-lived nitrous oxide will affect climate for a much longer time. The lifetimes of the proposed CFC replacements range from 1 to 40 years; the longer-lived replacements are still potentially effective as agents of climate change. One example of this, HCFC-22 (with a 15-year lifetime), has a similar effect (when released in the same amount) as CFC-11 on a 20-year time-scale; but less over a 500-year time-scale.

Although carbon dioxide is the least effective greenhouse gas per kilogram emitted, its contribution to global warming, which depends on the product of the GWP and the amount emitted, is largest. In the example in the lower box on page 12, the effect over 100 years of emissions of greenhouse gases in 1990 are shown relative to carbon dioxide. This is illustrative; to compare the effect of different emission projections we have to sum the effect of emissions made in future years.

There are other technical criteria which may help policymakers to decide, in the event of emissions reductions being deemed necessary, which gases should be considered. Does the gas contribute in a major way to current, and future, climate forcing? Does it have a long lifetime, so earlier reductions in emissions would be more effective than those made later? And are its sources and sinks well enough known to decide which could be controlled in practice? The table above illustrates these factors.

## How much do we expect climate to change?

It is relatively easy to determine the direct effect of the increased radiative forcing due to increases in greenhouse gases. However, as climate begins to warm, various processes act to amplify (through positive feedbacks) or reduce (through negative feedbacks) the warming. The main feedbacks which have been identified are due to changes in water vapour, sea-ice, clouds and the oceans.

The best tools we have which take the above feedbacks into account (but do not include greenhouse gas feedbacks) are three-dimensional mathematical models of the climate system (atmosphere ocean ice land), known as General Circulation Models (GCMs). They synthesize our knowledge of the physical and dynamical processes in the overall system and allow for the complex interactions between the various components. However, in their current state of development, the descriptions of many of the processes involved are comparatively crude. Because of this, considerable uncertainty is attached to these predictions of climate change, which is reflected in the range of values given; further details are given in a later section.

The estimates of climate change presented here are based on

i) the "best estimate" of equilibrium climate sensitivity (i.e. the equilibrium temperature change due to a doubling of carbon dioxide in the atmosphere) obtained from model simulations, feedback analyses and observational considerations (see later box: "What tools do we use...?")

ii) a "box diffusion upwelling" ocean atmosphere climate model which translates the greenhouse forcing into the evolution of the temperature response for the prescribed climate sensitivity. (This simple model has been calibrated against more complex ocean atmosphere coupled GCMs

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for situations where the more complex models have been run).

## How quickly will global climate change?

### a. If emissions follow a Business-as-Usual pattern

Under the IPCC Business-as-Usual (Scenario A) emissions of greenhouse gases, the average rate of increase of global mean temperature during the next century is estimated to be about 0.3°C per decade (with an uncertainty range of 0.2°C to 0.5°C). This will result in a likely increase in global mean temperature of about 1°C above the present value (about 2°C above that in the pre-industrial period) by 2025 and 3°C above today's (about 4°C above pre-industrial) before the end of the next century.

The projected temperature rise out to the year 2100, with high, low and best-estimate climate responses, is shown in the diagram below. Because of other factors which influence climate, we would not expect the rise to be a steady one.

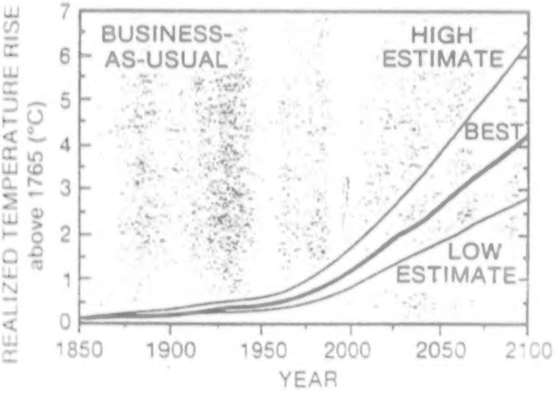
The temperature rises shown above are **realized** temperatures; at any time we would also be **committed** to a further temperature rise toward the equilibrium temperature (see box: "Equilibrium and realized climate change"). For the BaU "best-estimate" case in the year 2030, for example, a further 0.9°C rise would be expected, about 0.2°C of which would be realized by 2050 (in addition to changes due to further greenhouse gas increases); the rest would become apparent in decades or centuries.

Even if we were able to stabilize emissions of each of the greenhouse gases at present-day levels from now on, the temperature is predicted to rise by about 0.2°C per decade for the first few decades.

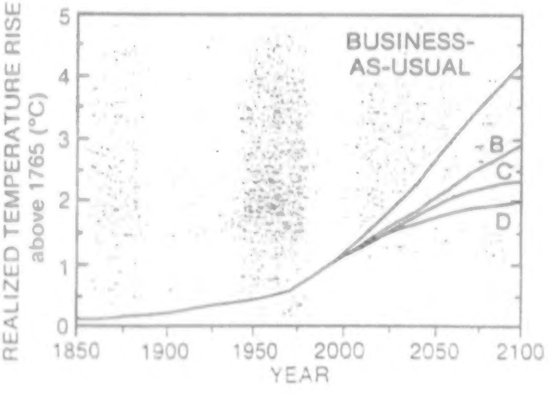
The global warming, will also lead to increased global average precipitation and evaporation of a few per cent by 2030. Areas of sea-ice and snow are expected to diminish.

### b. If emissions are subject to controls

Under the other IPCC emission scenarios which assume progressively increasing levels of controls, average rates of increase in global mean temperature over the next century are estimated to be about 0.2°C per decade (Scenario B), just above 0.1°C per decade (Scenario C) and about 0.1°C per decade (Scenario D). The results are illustrated below with the Business-as-Usual case for comparison. Only the best-estimate of the temperature rise is shown in each case. The indicated range of uncertainty in global temperature rise given above reflects a subjective assessment of uncertainties in the calculation of climate response, but does not include those due to the transformation of emissions to concentrations, nor the effects of greenhouse gas feedbacks.



Simulation of the increase in global mean temperature from 1850 to 1990 due to observed increases in greenhouse gases, and predictions of the rise between 1990 and 2100 resulting from the Business-as-Usual emissions.



Simulations of the increase in global mean temperature from 1850 to 1990 due to observed increases in greenhouse gases, and predictions of the rise between 1990 and 2100 resulting from the IPCC Scenario B, C and D emissions, with the Business-as-Usual case for comparison.

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## What tools do we use to predict future climate, and how do we use them?

The most highly developed tool which we have to predict future climate is known as a **general circulation model or GCM.** These models are based on the laws of physics and use descriptions in simplified physical terms (called parametrizations) of the smaller-scale processes such as those due to clouds and deep mixing in the ocean. In a climate model an atmospheric component, essentially the same as a weather prediction model, is coupled to a model of the ocean, which can be equally complex.

Climate forecasts are derived in a different way from weather forecasts. A weather prediction model gives a description of the atmosphere's state up to 10 days or so ahead, starting from a detailed description of an initial state of the atmosphere at a given time. Such forecasts describe the movement and development of large weather systems, though they cannot represent very small-scale phenomena; for example, individual shower clouds.

To make a climate forecast, the climate model is first run for a few (simulated) decades. The statistics of the model's output is a description of the model's simulated climate which, if the model is a good one, will bear a close resemblance to the climate of the real atmosphere and ocean. The above exercise is then repeated with increasing concentrations of the greenhouse gases in the model. The differences between the statistics of the two simulations (for example in mean temperature and interannual variability) provide an estimate of the accompanying climate change.

The long-term change in **surface air temperature** following a doubling of carbon dioxide (referred to as the **climate sensitivity**) is generally used as a bench-mark to compare models. The range of results from model studies is 1.9 to 5.2°C. Most results are close to 4.0°C but recent studies using a more detailed but not necessarily more accurate representation of cloud processes give results in the lower half of this range. Hence the models results do not justify altering the previously accepted range of 1.5 to 4.5°C.

Although scientists are reluctant to give a single best estimate in this range, it is necessary for the presentation of climate predictions for a choice of best estimate to be made. Taking into account the model results, together with observational evidence over the last century which is suggestive of the climate sensitivity being in the lower half of the range (see section: "Has man already begun to change the global climate?" on page 20) a value of climate sensitivity of 2.5°C has been chosen as the best estimate.

In this Assessment, we have also used much simpler models, which simulate the behaviour of GCMs, to make predictions of the evolution with time of global temperature from a number of emission scenarios. These so-called box-diffusion models contain highly simplified physics but give similar results to GCMs when globally averaged.

A completely different, and potentially useful, way of predicting patterns of future climate is to search for periods in the past when the global mean temperatures were similar to those we expect in future, and then use the past spatial patterns as **analogues** of those which will arise in the future. For a good analogue, it is also necessary for the forcing factors (for example, greenhouse gases, orbital variations) and other conditions (for example, ice cover, topography, etc.) to be similar; direct comparisons with climate situations for which these conditions do not apply cannot be easily interpreted. Analogues of future greenhouse-gas-changed climates have not been found.

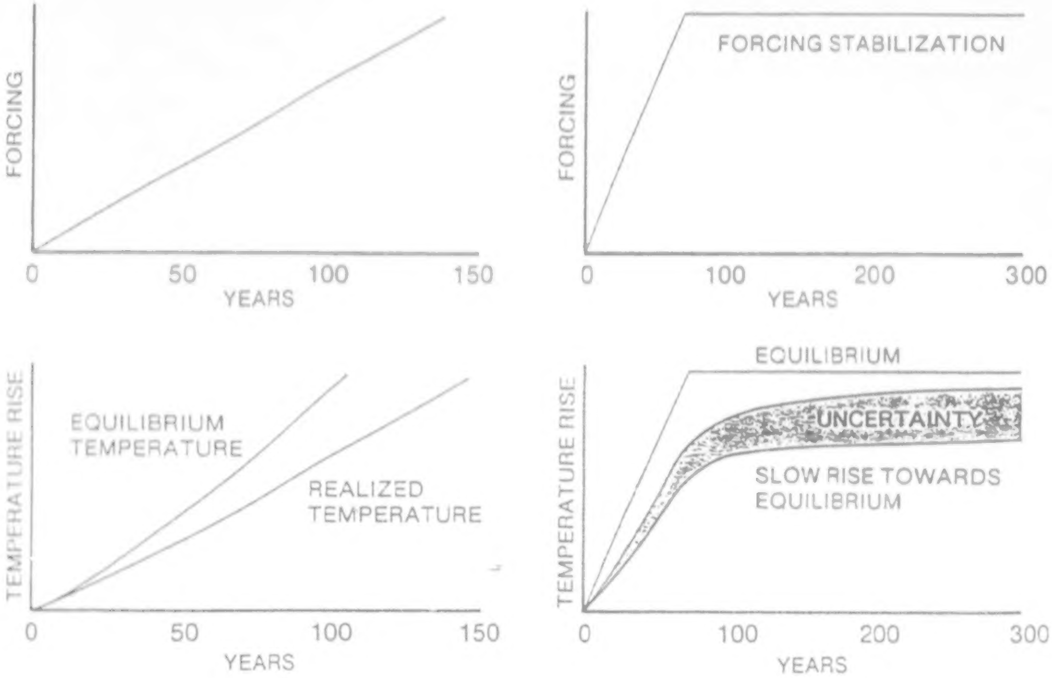
We cannot therefore advocate the use of palaeoclimates as predictions of regional climate change due to future increases in greenhouse gases. However, palaeoclimatological information can provide useful insights into climate processes, and can assist in the validation of climate models.

## Equilibrium and realized climate change

When the radiative forcing on the earth–atmosphere system is changed, for example by increasing greenhouse gas concentrations, the atmosphere will try to respond (by warming) immediately. But the atmosphere is closely coupled to the oceans, so in order for the air to be warmed by the greenhouse effect, the oceans also have to be warmed; because of their thermal capacity this takes decades or centuries. This exchange of heat between atmosphere and ocean will act to slow down the temperature rise forced by the greenhouse effect.

In a hypothetical example where the concentration of greenhouse gases in the atmosphere, following a period of constancy, rises suddenly to a new level and remains there, the radiative forcing would also rise rapidly to a new level. This increased radiative forcing would cause the atmosphere and oceans to warm, and eventually come to a new, stable, temperature. A commitment to this **equilibrium** temperature rise is incurred as soon as the greenhouse gas concentration changes. But at any time before equilibrium is reached, the actual temperature will have risen by only part of the equilibrium temperature change, known as the **realized** temperature change.

Models predict that, for the present-day case of an increase in radiative forcing which is approximately steady, the realized temperature rise at any time is about 50% of the committed temperature rise if the climate sensitivity (the response to a doubling of carbon dioxide) is 4.5°C and about 80% if the climate sensitivity is 1.5°C. If the forcing were then held constant, temperatures would continue to rise slowly, but it is not certain whether it would take decades or centuries for most of the remaining rise to equilibrium to occur.



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## What will be the patterns of climate change by 2030?

Knowledge of the global mean warming and change in precipitation is of limited use in determining the impacts of climate change, for instance on agriculture. For this we need to know changes regionally and seasonally.

Models predict that surface air will warm faster over land than over oceans, and a minimum of warming will occur around Antarctica and in the northern North Atlantic region.

There are some continental-scale changes which are consistently predicted by the highest-resolution models and for which we understand the physical reasons. The warming is predicted to be 50–100% greater than the global mean in high northern latitudes in winter, and substantially smaller than the global mean in regions of sea-ice in summer. Precipitation is predicted to increase on average in middle and high latitude continents in winter (by some 5–10% over 35–55°N).

Five regions, each a few million square kilometres in area and representative of different climatological regimes, were selected by IPCC for particular study. In the box on page 18 are given the changes in temperature, precipitation and soil moisture, which are predicted to occur by 2030 on the Business-as-Usual scenario, as an average over each of the five regions. There may be considerable variations within the regions. In general, confidence in these regional estimates is low, especially for the changes in precipitation and soil moisture, but they are examples of our best estimates. We cannot yet give reliable regional predictions at the smaller scales demanded for impacts assessments.

## How will climate extremes and extreme events change?

Changes in the variability of weather and the frequency of extremes will generally have more impact than changes in the mean climate at a particular location. With the possible exception of an increase in the number of intense showers, there is no clear evidence that weather variability will change in the future. In the case of temperatures, assuming no change in variability, but with a modest increase in the mean, the number of days with temperatures above a given value at the high end of the distribution will increase substantially. On the same assumptions, there will be a decrease in days with temperatures at the low end of the distribution. So the number of very hot days or frosty nights can be substantially changed without any change in the variability of the weather. The number of days with a minimum threshold amount of soil moisture (for viability of a certain crop, for example) would be even more sensitive to changes in average precipitation and evaporation.

If the large-scale weather regimes, for instance depression tracks or anticyclones, shift their position, this would effect the variability and extremes of weather at a particular location, and could have a major effect. However, we do not know if, or in what way, this will happen.

## Will storms increase in a warmer world?

Storms can have a major impact on society. Will their frequency, intensity or location increase in a warmer world?

**Tropical storms**, such as typhoons and hurricanes, only develop at present over seas that are warmer than about 26°C. Although the area of sea having temperatures over this critical value will increase as the globe warms, the critical temperature itself may increase in a warmer world. Although the theoretical maximum intensity is expected to increase with temperature, climate models give no consistent indication whether tropical storms will increase or decrease in frequency or intensity as climate changes; neither is there any evidence that this has occurred over the past few decades.

**Mid-latitude storms**, such as those which track across the North Atlantic and North Pacific, are driven by the equator-to-pole temperature contrast. As this contrast will probably be weakened in a warmer world (at least in the northern hemisphere), it might be argued that mid-latitude storms will also weaken or change their tracks, and there is some indication of a general reduction in day-to-day variability in the mid-latitude storm tracks in winter in model simulations, though the pattern of changes vary from model to model. Present models do not resolve smaller-scale disturbances, so it will not be possible to assess changes in storminess until results from higher-resolution models become available in the next few years.

## Climate change in the longer term

The foregoing calculations have focused on the period up to the year 2100; it is clearly more difficult to make calculations for years beyond 2100. However, while the timing of a predicted increase in global temperatures has substantial uncertainties, the prediction that an increase will eventually occur is more certain. Furthermore, some model calculations that have been extended beyond

## ESTIMATES FOR CHANGES BY 2030

(IPCC Business-as-Usual scenario; changes from **pre-industrial**)

The numbers given below are based on high-resolution models, scaled to be consistent with our best estimate of global mean warming of 1.8°C by 2030. For values consistent with other estimates of global temperature rise, the numbers below should be reduced by 30% for the low estimate or increased by 50% for the high estimate. Precipitation estimates are also scaled in a similar way.

### Confidence in these regional estimates is low

**Central North America (35°–50°N 85°–105°W)**

The warming varies from 2 to 4°C in winter and 2 to 3°C in summer. Precipitation increases range from 0 to 15% in winter whereas there are decreases of 5 to 10% in summer. Soil moisture decreases in summer by 15 to 20%.

**Southern Asia (5°–30°N 70°–105°E)**

The warming varies from 1 to 2°C throughout the year. Precipitation changes little in winter and generally increases throughout the region by 5 to 15% in summer. Summer soil moisture increases by 5 to 10%.

**Sahel (10°–20°N 20°W–40°E)**

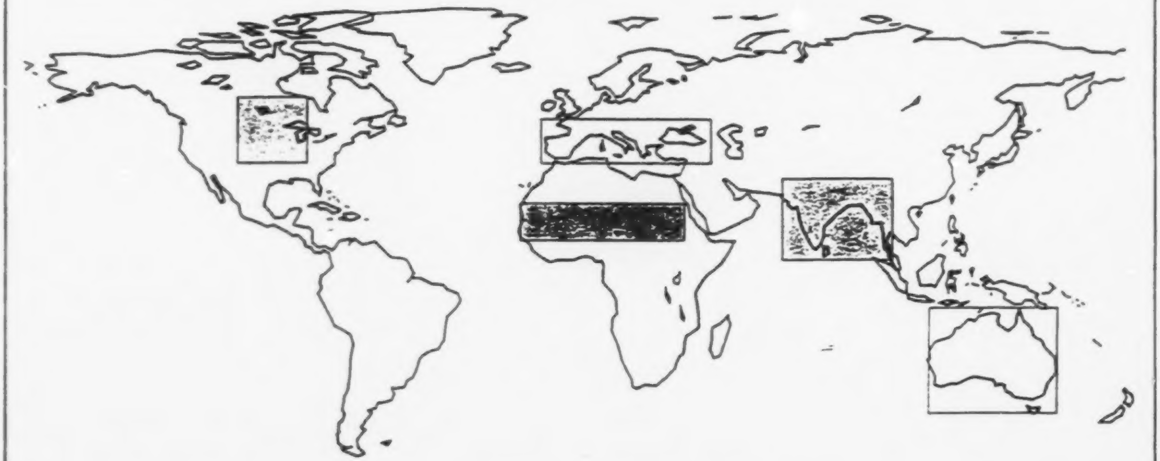
The warming ranges from 1 to 3°C. Area mean precipitation increases and area mean soil moisture decreases marginally in summer. However, throughout the region, there are areas of both increase and decrease in both parameters throughout the region.

**Southern Europe (35°–50°N 10°W–45°E)**

The warming is about 2°C in winter and varies from 2 to 3°C in summer. There is some indication of increased precipitation in winter, but summer precipitation decreases by 5 to 15%, and summer soil moisture by 15 to 25%.

**Australia (12°–45°S 110°–155°E)**

The warming ranges from 1 to 2°C in summer and is about 2°C in winter. Summer precipitation increases by around 10%, but the models do not produce consistent estimates of the changes in soil moisture. The area averages hide large variations at the sub-continental level.



Map showing the locations and extents of the five areas selected by IPCC

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100 years suggest that, with continued increases in greenhouse climate forcing, there could be significant changes in the ocean circulation, including a decrease in North Atlantic deep water formation.

### Other factors which could influence future climate

Variations in the output of **solar energy** may also affect climate. On a decadal time-scale solar variability and changes in greenhouse gas concentration could give changes of similar magnitudes. However, the variation in solar intensity changes sign so that over longer time-scales the increases in greenhouse gases are likely to be more important. **Aerosols** as a result of volcanic eruptions can lead to a cooling at the surface which may oppose the greenhouse warming for a few years following an eruption. Again, over longer periods the greenhouse warming is likely to dominate.

Human activity is leading to an increase in aerosols in the lower atmosphere, mainly from sulphur emissions. These have two effects, both of which are difficult to quantify but which may be significant particularly at the regional level. The first is the direct effect of the aerosols on the radiation scattered and absorbed by the atmosphere. The second is an indirect effect whereby the aerosols affect the microphysics of clouds leading to an increased cloud reflectivity. Both these effects might lead to a significant regional cooling; a decrease in emissions of sulphur might be expected to increase global temperatures.

Because of long-period couplings between different components of the climate system, for example between ocean and atmosphere, the Earth's climate would still vary without being perturbed by any external influences. This **natural variability** could act to add to, or subtract from, any human-made warming; on a century time-scale this would be less than changes expected from greenhouse gas increases.

## How much confidence do we have in our predictions?

Uncertainties in the above climate predictions arise from our imperfect knowledge of:

- future rates of human-made emissions
- how these will change the atmospheric concentrations of greenhouse gases
- the response of climate to these changed concentrations

Firstly, it is obvious that the extent to which climate will change depends on the rate at which greenhouse gases (and other gases which affect their concentrations) are emitted. This in turn will be determined by various complex economic and sociological factors. Scenarios of future emissions were generated within IPCC WG III and are described in the Annex.

Secondly, because we do not fully understand the sources and sinks of the greenhouse gases, there are uncertainties in our calculations of future concentrations arising from a given emissions scenario. We have used a number of models to calculate concentrations and chosen a best estimate for each gas. In the case of carbon dioxide, for example, the concentration increase between 1990 and 2070 due to the Business-as-Usual emissions scenario spanned almost a factor of two between the highest and lowest model result (corresponding to a range in radiative forcing change of about 50%).

Furthermore, because natural sources and sinks of greenhouse gases are sensitive to a change in climate, they may substantially modify future concentrations (see earlier section: "Greenhouse gas feedbacks" on page 10). It appears that, as climate warms, these feedbacks will lead to an overall increase, rather than decrease, in natural greenhouse gas abundances. For this reason, climate change is likely to be greater than the estimates we have given.

Thirdly, climate models are only as good as our understanding of the processes which they describe, and this is far from perfect. The ranges in the climate predictions given above reflect the uncertainties due to model imperfections; the largest of these is cloud feedback (those factors affecting the cloud amount and distribution and the interaction of clouds with solar and terrestrial radiation), which leads to a factor of two uncertainty in the size of the warming. Others arise from the transfer of energy between the atmosphere and ocean, the atmosphere and land surfaces, and between the upper and deep layers of the ocean. The treatment of sea-ice and convection in the models is also crude. Nevertheless, for reasons given in the box on page 20, we have substantial confidence that models can predict at least the broad-scale features of climate change.

Furthermore, we must recognize that our imperfect understanding of climate processes (and corresponding ability to model them) could make us vulnerable to surprises; just as the human-made ozone hole over Antarctica was entirely unpredicted. In particular, the ocean circulation, changes in which are thought to have led to periods of comparatively rapid climate change at the end of the last ice age, is not well observed, understood or modelled.

## Will the climate of the future be very different?

When considering future climate change, it is clearly essential to look at the record of climate variation in the past. From it we can learn about the range of natural climate variability, to see how it compares with what we expect in the future, and also look for evidence of recent climate change due to man's activities.

Climate varies naturally on all time-scales from hundreds of millions of years down to the year to year. Prominent in the Earth's history have been the 100,000-year glacial-interglacial cycles when climate was mostly cooler than at present. Global surface temperatures have typically varied by 5–7°C through these cycles, with large changes in ice volume and sea level, and temperature changes as great as 10–15°C in some middle and high latitude regions of the northern hemisphere. Since the end of the last ice age, about 10,000 years ago, global surface temperatures have probably fluctuated by little more than 1°C. Some fluctuations have lasted several centuries, including the Little Ice Age which ended in the nineteenth century and which appears to have been global in extent.

The changes predicted to occur by about the middle of the next century due to increases in greenhouse gas concentrations from the Business-as-Usual emissions will make global mean temperatures higher than they have been for 150,000 years.

The **rate of change** of global temperatures predicted for Business-as-Usual emissions will be greater than those which have occurred naturally on Earth over the last 10,000 years, and the rise in sea level will be about three to six times faster than that seen over the last 100 years or so.

## Confidence in predictions from climate models

What confidence can we have that climate change due to increasing greenhouse gases will look anything like the model predictions? Weather forecasts can be compared with the actual weather the next day and their skill assessed; we cannot do that with climate predictions. However, there are several indicators that give us some confidence in the predictions from climate models.

When the latest atmospheric models are run with the present atmospheric concentrations of greenhouse gases and observed boundary conditions, their simulation of present climate is generally realistic on large scales, capturing the major features such as the wet tropical convergence zones and mid-latitude depression belts, as well as the contrasts between summer and winter circulations. The models also simulate the observed variability; for example, the large day-to-day pressure variations in the middle-latitude depression belts and the maxima in interannual variability responsible for the very different character of one winter from another both being represented. However, on regional scales (2,000 km or less), there are significant errors in all models.

Overall confidence is increased by atmospheric models generally satisfactory portrayal of aspects of variability of the atmosphere, for instance those associated with variations in sea surface temperature. There has been some success in simulating the general circulation of the ocean, including the patterns (though not always the intensities) of the principal currents, and the distributions of tracers added to the ocean.

Atmospheric models have been coupled with simple models of the ocean to predict the equilibrium response to greenhouse gases, under the assumption that the model errors are the same in a changed climate. The ability of such models to simulate important aspects of the climate of the last ice age generates confidence in their usefulness. Atmospheric models have also been coupled with multi-layer ocean models (to give coupled ocean–atmosphere GCMs) which predict the gradual response to increasing greenhouse gases. Although the models so far are of relatively coarse resolution, the large-scale structures of the ocean and the atmosphere can be simulated with some skill. However, the coupling of ocean and atmosphere models reveals a strong sensitivity to small-scale errors which leads to a drift away from the observed climate. As yet, these errors must be removed by adjustments to the exchange of heat between ocean and atmosphere. There are similarities between results from the coupled models using simple representations of the ocean and those using more sophisticated descriptions, and our understanding of such differences as do occur gives us some confidence in the results.

## Has man already begun to change the global climate?

The instrumental record of surface temperature is fragmentary until the mid nineteenth century, after which it slowly improves. Because of different methods of measurement, historical records have to be harmonized with modern observations, introducing some uncertainty. Despite these problems we believe that a real warming of the globe of 0.3 to 0.6°C has taken place over the last century; any bias due to urbanization is likely to be less than 0.05°C.

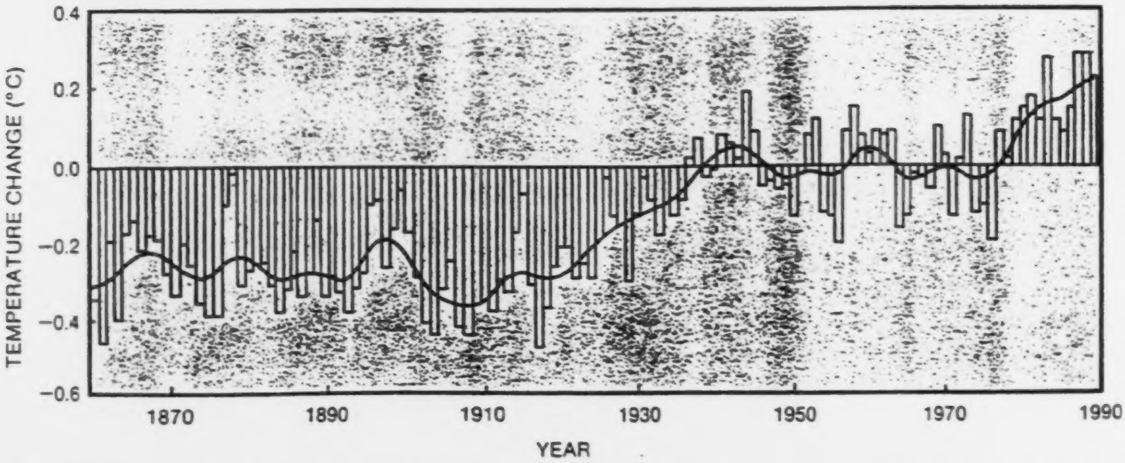
Moreover, since 1900 similar temperature increases are seen in three independent data sets: one collected over land and two over the oceans. The figure below shows current estimates of smoothed global mean surface temperature over land and ocean since 1860. Confidence in the record has been increased by their similarity to recent satellite measurements of mid-tropospheric temperatures.

Although the overall temperature rise has been broadly similar in both hemispheres, it has not been steady, and differences in their rates of warming have sometimes persisted for decades. Much of the warming since 1900 has been concentrated in two periods, the first between about 1910 and 1940 and the other since 1975; the five warmest years on record have all been in the 1980s. The northern hemisphere cooled between the 1940s and the early 1970s when southern hemisphere temperatures stayed nearly constant. The pattern of global warming since 1975 has been uneven with some regions, mainly in the northern hemisphere, continuing to cool until recently. This regional diversity indicates that future regional temperature changes are likely to differ considerably from a global average.

The conclusion that global temperature has been rising is strongly supported by the retreat of most **mountain glaciers** of the world since the end of the nineteenth century and the fact that global **sea level** has risen over the same period by an average of 1 to 2mm per year. Estimates of thermal expansion of the oceans, and of increased melting of mountain glaciers and the ice margin in west Greenland over the last century, show that the major part of the sea level rise appears to be related to the observed global warming. This apparent connection between observed sea level rise and global warming provides grounds for believing that future warming will lead to an acceleration in sea level rise.

The size of the warming over the last century is broadly consistent with the predictions of climate models, but is also of the same magnitude as natural climate variability. If the sole cause of the observed warming were the man-made greenhouse effect, then the implied climate sensitivity would be near the lower end of the range inferred from the models. The observed increase could be largely due to natural variability; alternatively this variability and other man-made factors could have offset a still larger man-made greenhouse warming. The unequivocal detection of the enhanced greenhouse effect from observations is not likely for a decade or more, when the commitment to future climate change will then be considerably larger than it is today.

Global-mean temperature alone is an inadequate indicator of greenhouse-gas-induced climatic change. Identifying the causes of any global mean temperature change requires examination of other aspects of the changing climate, particularly its spatial and temporal characteristics — the man-made climate change "signal". Patterns of climate change from models such as the northern hemisphere



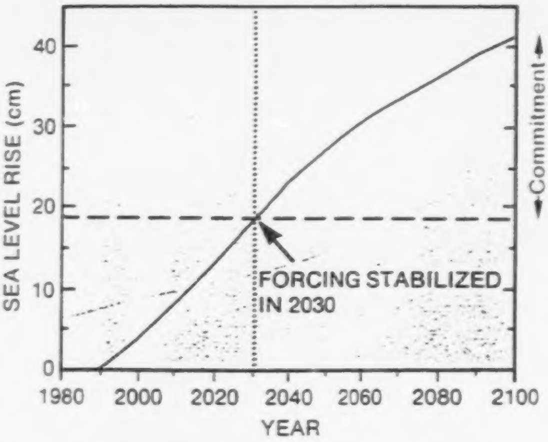
**Annual deviation of global mean combined land-air and sea-surface temperatures for the period 1861–1989 (shown by bars), relative to the average for 1951–1980. The curve shows the results of a smoothing filter applied to the annual values.**

warming faster than the southern hemisphere, and surface air warming faster over land than over oceans, are not apparent in observations to date. However, we do not yet know what the detailed "signal" looks like because we have limited confidence in our predictions of climate change patterns. Furthermore, any changes to date could be masked by natural variability and other (possibly man-made) factors, and we do not have a clear picture of these.

## How much will sea level rise?

Simple models were used to calculate the rise in sea level to the year 2100; the results are illustrated here. The calculations necessarily ignore any long-term changes, unrelated to greenhouse forcing, that may be occurring but cannot be detected from the present data on land-ice and the ocean. The sea level rise expected from 1990–2100 under the IPCC Business-as-Usual emissions scenario is shown below; an average rate of global mean sea level rise of about 6 cm per decade over the next century (with an uncertainty range of 3–10 cm per decade). The predicted rise is about 20 cm in global mean sea level by 2030, and 65 cm by the end of the next century. There will be significant regional variations.

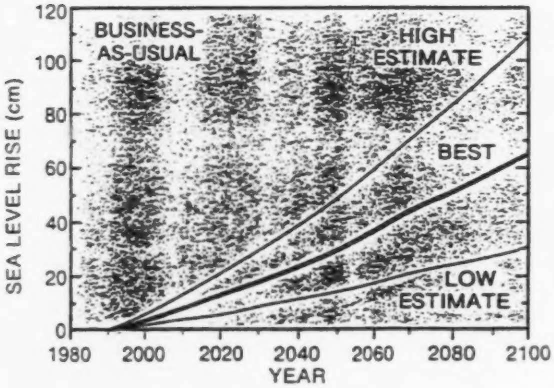
The best estimate in each case is made up mainly of positive contributions from thermal expansion of the oceans and the melting of glaciers. Although, over the next 100 years, the effect of the Antarctic and Greenland ice sheets is expected to be small, they make a major contribution to the uncertainty in predictions.



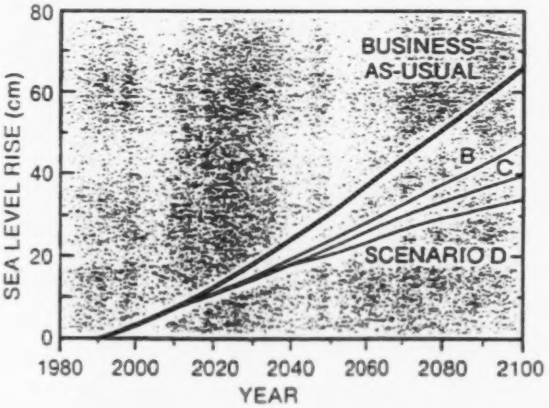
**Commitment to sea level rise in the year 2030. The curve shows the sea level rise due to Business-as-Usual emissions to 2030, with the additional rise that would occur in the remainder of the century even if climate forcing was stabilized in 2030.**

Even if greenhouse forcing increased no further, there would still be a commitment to a continuing sea level rise for many decades and even centuries, due to delays in climate, ocean and ice mass responses. As an illustration, if the increases in greenhouse gas concentrations were to suddenly stop in 2030, sea level would go on rising from 2030 to 2100, by as much again as from 1990–2030, as shown in the diagram above.

Predicted sea level rises due to the other three emissions scenarios are shown below, with the Business-as-Usual case for comparison; only best-estimate calculations are shown.



**Sea level rise predicted to result from Business-as-Usual emissions, showing the best-estimate and range.**



**Model estimates of sea level rise from 1990 to 2100 due to all four emissions scenarios.**

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The West Antarctic Ice Sheet is of special concern. A large portion of it, containing an amount of ice equivalent to about 5m of global sea level, is grounded far below sea level. There have been suggestions that a sudden outflow of ice might result from global warming and raise sea level quickly and substantially. Recent studies have shown that individual ice streams are changing rapidly on a decade-to-century time-scale; however, this is not necessarily related to climate change. Within the next century, it is not likely that there will be a major outflow of ice from West Antarctica due directly to global warming.

Any rise in sea level is not expected to be uniform over the globe. Thermal expansion, changes in ocean circulation, and surface air pressure will vary from region to region as the world warms, but in an as yet unknown way. Such regional details await further development of more realistic coupled ocean atmosphere models. In addition, vertical land movements can be as large or even larger than changes in global mean sea level; these movements have to be taken into account when predicting local change in sea level relative to land.

The most severe effects of sea level rise are likely to result from extreme events (for example, storm surges) the incidence of which may be affected by climatic change.

## What will be the effect of climate change on ecosystems?

Ecosystem processes such as photosynthesis and respiration are dependent on climatic factors and carbon dioxide concentration in the short term. In the longer term, climate and carbon dioxide are among the factors which control ecosystem structure, i.e. species composition, either directly by increasing mortality in poorly adapted species, or indirectly by mediating the competition between species. Ecosystems will respond to local changes in temperature (including its rate of change), precipitation, soil moisture and extreme events. Current models are unable to make reliable estimates of changes in these parameters on the required local scales.

Photosynthesis captures atmospheric carbon dioxide, water and solar energy and stores them in organic compounds which are then used for subsequent plant growth, the growth of animals or the growth of microbes in the soil. All of these organisms release carbon dioxide via respiration into the atmosphere. Most land plants have a system of photosynthesis which will respond positively to increased atmospheric carbon dioxide ("the carbon dioxide fertilization effect") but the response varies with species. The effect may decrease with time when restricted by other ecological limitations, for example, nutrient availability. It should be emphasized that the carbon content of the terrestrial biosphere will increase only if the forest ecosystems in a state of maturity will be able to store more carbon in a warmer climate and at higher concentrations of carbon dioxide. We do not yet know if this is the case.

The response to increased carbon dioxide results in greater efficiencies of water, light and nitrogen use. These increased efficiencies may be particularly important during drought and in arid/semi-arid and infertile areas.

Because species respond differently to climatic change, some will increase in abundance and/or range while others will decrease. Ecosystems will therefore change in structure and composition. Some species may be displaced to higher latitudes and altitudes, and may be more prone to local, and possibly even global, extinction; other species may thrive.

As stated above, ecosystem structure and species distribution are particularly sensitive to the rate of change of climate. We can deduce something about how quickly global temperature has changed in the past from palaeoclimatological records. As an example, at the end of the last glaciation, within about a century, temperature increased by up to 5°C in the North Atlantic region, mainly in western Europe. Although during the increase from the glacial to the current interglacial temperature simple tundra ecosystems responded positively, a similar rapid temperature increase applied to more developed ecosystems could result in their instability.

## What should be done to reduce uncertainties, and how long will this take?

Although we can say that some climate change is unavoidable, much uncertainty exists in the prediction of global climate properties such as the temperature and rainfall. Even greater uncertainty exists in predictions of regional climate change, and the subsequent consequences for sea level and ecosystems. The key areas of scientific uncertainty are:

- **clouds**: primarily cloud formation, dissipation, and radiative properties, which influence the response of the atmosphere to greenhouse forcing;

## Deforestation and Reforestation

Man has been deforesting the Earth for millennia. Until the early part of the century, this was mainly in temperate regions, more recently it has been concentrated in the tropics. Deforestation has several potential impacts on climate: through the carbon and nitrogen cycles (where it can lead to changes in atmospheric carbon dioxide concentrations), through the change in reflectivity of terrain when forests are cleared, through its effect on the hydrological cycle (precipitation, evaporation and runoff) and surface roughness and thus atmospheric circulation which can produce remote effects on climate.

It is estimated that each year about 2 Gt of carbon (GtC) is released to the atmosphere due to tropical deforestation. The rate of forest clearing is difficult to estimate; probably until the mid-20th century, temperate deforestation and the loss of organic matter from soils was a more important contributor to atmospheric carbon dioxide than was the burning of fossil fuels. Since then, fossil fuels have become dominant; one estimate is that around 1980, 1.6GtC was being released annually from the clearing of tropical forests, compared with about 5GtC from the burning of fossil fuels. If all the tropical forests were removed, the input is variously estimated at from 150 to 240GtC; this would increase atmospheric carbon dioxide by 35 to 60ppmv.

To analyse the effect of reforestation we assume that 10 million hectares of forests are planted each year for a period of 40 years, i.e. 4 million km$^2$ would then have been planted by 2030, at which time 1GtC would be absorbed annually until these forests reach maturity. This would happen in 40–100 years for most forests. The above scenario implies an accumulated uptake of about 20GtC by the year 2030 and up to 80GtC after 100 years. This accumulation of carbon in forests is equivalent to some 5–10% of the emission due to fossil fuel burning in the Business-as-Usual scenario.

Deforestation can also alter climate directly by increasing reflectivity and decreasing evapotranspiration. Experiments with climate models predict that replacing all the forests of the Amazon Basin by grassland would reduce the rainfall over the basin by about 20%, and increase mean temperature by several degrees.

- **oceans:** the exchange of energy between the ocean and the atmosphere, between the upper layers of the ocean and the deep ocean, and transport within the ocean, all of which control the rate of global climate change and the patterns of regional change;
- **greenhouse gases:** quantification of the uptake and release of the greenhouse gases, their chemical reactions in the atmosphere, and how these may be influenced by climate change;
- **polar ice sheets:** which affect predictions of sea level rise.

Studies of land surface hydrology, and of impact on ecosystems, are also important.

To reduce the current scientific uncertainties in each of these areas will require internationally co-ordinated research, the goal of which is to improve our capability to observe, model and understand the global climate system. Such a programme of research will reduce the scientific uncertainties and assist in the formulation of sound national and international response strategies.

Systematic long-term **observations** of the system are of vital importance for understanding the natural variability of the Earth's climate system, detecting whether man's activities are changing it, parametrizing key processes for models, and verifying model simulations. Increased accuracy and coverage in many observations are required. Associated with expanded observations is the need to develop appropriate comprehensive global information bases for the rapid and efficient dissemination and utilization of data. The main observational requirements are:

i) the maintenance and improvement of observations (such as those from satellites) provided by the World Weather Watch Programme of WMO,

ii) the maintenance and enhancement of a programme of monitoring, both from satellite-based and surface-based instruments, of key climate elements for which accurate observations on a continuous basis are required, such as the distribution of important atmospheric constituents, clouds, the Earth's radiation budget, precipitation, winds, sea surface temperatures and terrestrial ecosystem extent, type and productivity,

ii) the establishment of a global ocean observing system to measure changes in such variables as ocean surface topography, circulation, transport of heat and chemicals, and sea-ice extent and thickness.

iv) the development of major new systems to obtain data on the oceans, atmosphere and terrestrial ecosystems using both satellite-based instruments and instruments based on the surface, on automated instrumented vehicles in the ocean, on floating and deep sea buoys, and on aircraft and balloons, and

v) the use of palaeoclimatological and historical instrumental records to document natural variability and changes in the climate system, and subsequent environmental response.

The **modelling** of climate change requires the development of global models which couple together atmosphere, land, ocean and ice models and which incorporate more realistic formulations of the relevant processes and the interactions between the different components. Processes in the biosphere (both on land and in the ocean) also need to be included. Higher spatial resolution than is currently generally used is required if regional patterns are to be predicted. These models will require the largest computers which are planned to be available during the next decades.

**Understanding** of the climate system will be developed from analyses of observations and of the results from model simulations. In addition, detailed studies of particular processes will be required through targetted observational campaigns. Examples of such field campaigns include combined observational and small-scale modelling studies for different regions, of the formation, dissipation, radiative, dynamical and microphysical properties of clouds, and ground-based (ocean and land) and aircraft measurements of the fluxes of greenhouse gases from specific ecosystems. In particular, emphasis must be placed on field experiments that will assist in the development and improvement of sub-grid-scale parametrizations for models.

The required programme of research will require unprecedented international co-operation, with the World Climate Research Programme (WCRP) of the World Meteorological Organization and International Council of Scientific Unions (ICSU), and the International Geosphere-Biosphere Programme (IGBP) of ICSU both playing vital roles. These are large and complex endeavours that will require the involvement of all nations, particularly the developing countries. Implementation of existing and planned projects will require increased financial and human resources; the latter requirement has immediate implications at all levels of education, and the international community of scientists needs to be widened to include more members from developing countries.

The WCRP and IGBP have a number of ongoing or planned research programmes, that address each of the three key areas of scientific uncertainty. Examples include:

- **clouds:**
  International Satellite Cloud Climatology Project (ISCCP);
  Global Energy and Water Cycle Experiment (GEWEX).
- **oceans:**
  World Ocean Circulation Experiment (WOCE);
  Tropical Oceans and Global Atmosphere (TOGA).
- **trace gases:**
  Joint Global Ocean Flux Study (JGOFS);
  International Global Atmospheric Chemistry (IGAC);
  Past Global Changes (PAGES).

As research advances, increased understanding and improved observations will lead to progressively more reliable climate predictions. However, considering the complex nature of the problem and the scale of the scientific programmes to be undertaken we know that rapid results cannot be expected. Indeed further scientific advances may expose unforeseen problems and areas of ignorance.

Time-scales for narrowing the uncertainties will be dictated by progress over the next 10–15 years in two main areas:

- Use of the fastest possible computers, to take into account coupling of the atmosphere and the oceans in models, and to provide sufficient resolution for regional predictions.
- Development of improved representation of small-scale processes within climate models, as a result of the analysis of data from observational programmes to be conducted on a continuing basis well into the next century.

# ANNEX

## Emissions Scenarios From Working Group III Of The Intergovernmental Panel On Climate Change

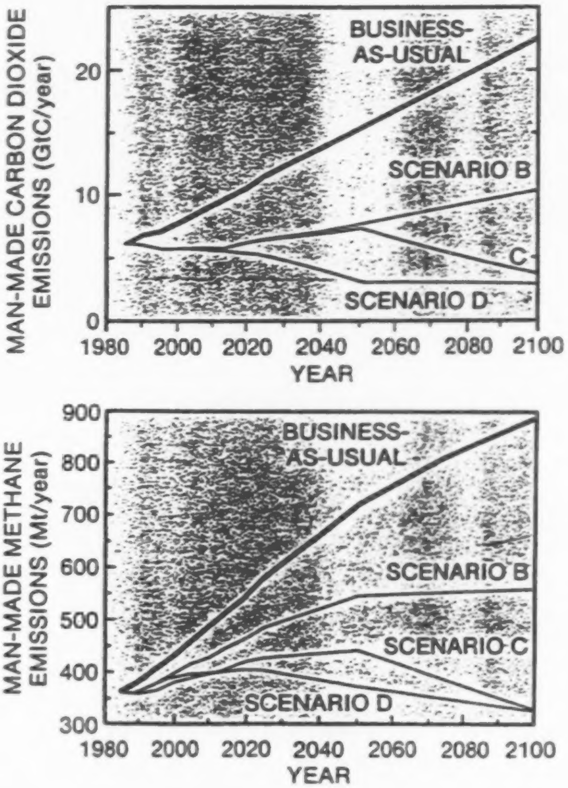
The Steering Group of the Response Strategies Working Group requested the USA and The Netherlands to develop emissions scenarios for evaluation by the IPCC Working Group I. The scenarios cover the emissions of carbon dioxide ($CO_2$), methane ($CH_4$), nitrous oxide ($N_2O$), chlorofluorocarbons (CFCs), carbon monoxide (CO) and nitrogen oxides ($NO_x$) from the present up to the year 2100. Growth of the economy and population was taken common for all scenarios. Population was assumed to approach 10.5 billion in the second half of the next century. Economic growth was assumed to be 2–3% annually in the coming decade in the OECD countries and 3–5% in the eastern European and developing countries. The economic growth levels were assumed to decrease thereafter. In order to reach the required targets, levels of technological development and environmental controls were varied.

In the **Business-as-Usual scenario** (Scenario A) the energy supply is coal intensive and on the demand side only modest efficiency increases are achieved. Carbon monoxide controls are modest, deforestation continues until the tropical forests are depleted and agricultural emissions of methane and nitrous oxide are uncontrolled. For CFCs the Montreal Protocol is implemented albeit with only partial participation. Note that the aggregation of national projections by IPCC Working Group III gives higher emissions (10–20%) of carbon dioxide and methane by 2025.

In **Scenario B** the energy supply mix shifts towards lower carbon fuels, notably natural gas. Large efficiency increases are achieved. Carbon monoxide controls are stringent, deforestation is reversed and the Montreal Protocol implemented with full participation.

In **Scenario C** a shift towards renewables and nuclear energy takes place in the second half of next century. CFCs are now phased out and agricultural emissions limited.

For **Scenario D** a shift to renewables and nuclear in the first half of the next century reduces the emissions of carbon dioxide, initially more or less stabilizing emissions in the industrialized countries. The scenario shows that stringent controls in industrialized countries combined with moderated growth of emissions in developing countries could stabilize atmospheric concentrations. Carbon dioxide emissions are reduced to 50% of 1985 levels by the middle of the next century.



**Man-made emissions of carbon dioxide and methane (as examples) to the year 2100, in the four scenarios developed by IPCC Working Group III.**

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# Energy and greenhouse gas emissions

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**The energy sector is the biggest contributor to man-made climate change.** Energy use is responsible for about three-quarters of mankind's carbon dioxide (CO2) emissions, one-fifth of our methane (CH4), and a significant quantity of our nitrous oxide (N2O). It also produces nitrogen oxides (NOx) hydro-carbons (HCs), and carbon monoxide (CO), which, though not greenhouse gases (GHGs) themselves, influence chemical cycles in the atmosphere that produce or destroy GHGs, such as tropospheric ozone.

**Most GHGs are released during the burning of fossil fuels.** Oil, coal, and natural gas supply the energy needed to run automobiles, heat houses, and power factories. In addition to energy, however, these fuels also produce various by-products. Carbon and hydrogen in the burning fuel combine with oxygen (O2) in the atmosphere to yield heat (which can be converted into other forms of useful energy) as well as water vapor and carbon dioxide. If the fuel burned completely, the only by-product containing carbon would be carbon dioxide. However, since combustion is often incomplete, other carbon-containing gases are also produced, including carbon monoxide, methane, and other hydrocarbons. In addition, nitrous oxide and other nitrogen oxides are produced as by-products when fuel combustion causes nitrogen from the fuel or the air to combine with oxygen from the air. Increases in tropospheric ozone are indirectly caused by fuel combustion as a result of reactions between pollutants caused by combustion and other gases in the atmosphere.

**Extracting, processing, transporting, and distributing fossil fuels can also release greenhouse gases.** These releases can be deliberate, as when natural gas is flared or vented from oil wells, emitting mostly methane and carbon dioxide, respectively. Releases can also result from accidents, poor maintenance, or small leaks in well heads and pipe fittings. Methane, which appears naturally in coal seams as pockets of gas or "dissolved" in the coal itself, is released when coal is mined or pulverized. Methane, hydrocarbons, and nitrogen oxides are emitted when oil and natural gas are refined into end products and when coal is processed (which involves crushing and washing) to remove ash, sulfur, and other impurities. Methane and smaller quantities of carbon dioxide and hydrocarbons are released from leaks in natural gas pipelines. Hydrocarbons are also released during the transport and distribution of liquid fuels in the form of oil spills from tanker ships, small losses during the routine fueling of motor vehicles, and so on.

**Some fuels produce more carbon dioxide per unit of energy than do others.** The amount of carbon dioxide emitted per unit of energy depends on the fuel's carbon and energy content. The figures below give representative values for coal, refined oil products, natural gas, and wood. Figure A shows for each fuel the percentage by weight that is elemental carbon. Figure B shows how many gigajoules (GJ) of energy are released when a tonne of fuel is burned. Figure C indicates how many kilograms of carbon are created (in the form of carbon dioxide) when each fuel is burned to yield a gigajoule of energy. According to Figure C, coal emits around 1.7 times as much carbon per unit of energy when burned as does natural gas and 1.25 times as much as oil.

**Although it produces a large amount of carbon dioxide, burning wood (and other biomass) contributes less to climate change than does burning fossil fuel.** In Figure C, wood appears to have the highest emission coefficient. However, while the carbon contained in fossil fuels has been stored in the earth for hundreds of millions of years and is now being rapidly released over mere decades, this is not the case with plants. When plants are burned as fuel, their carbon is recycled back into the atmosphere at roughly the same rate at which it was removed, and thus makes no *net* contribution to the pool of carbon dioxide in the air. Of course, when biomass is removed but is not allowed to grow back - as in the case of massive deforestation - the use of biomass fuels use *can* yield net carbon dioxide emissions.

**It is difficult to make precise calculations of the energy sector's greenhouse gas emissions.** Estimates of greenhouse gas emissions depend on the accuracy of the available energy statistics and on estimates of "emission factors", which attempt to describe how much of a gas is emitted per unit of fuel burned. Emission factors for carbon dioxide are well known, and the level of uncertainty in national CO2 emissions estimates are thus fairly low, probably around 10 percent. For the other gases, however, the emission factors are not so well understood, and estimates of national emissions may deviate from reality by a factor of two or more. Estimates of emissions from extracting, processing, transport, and so on are similarly uncertain.

See also Fact Sheet 240: "Reducing greenhouse gas emissions from the energy sector".

**For further reading:**

Grubb, M., 1989. "On Coefficients for Determining Greenhouse Gas Emissions from Fossil Fuel Production and Consumption". P. 537 in *Energy Technologies for Reducing Emissions of Greenhouse Gases. Proceedings of an Experts' Seminar, Volume 1*, OECD, Paris, 1989.

ORNL, 1989. *Estimates of CO2 Emissions from Fossil Fuel Burning and Cement Manufacturing. Based on the United Nations Energy Statistics and the U.S. Bureau of Mines Cement Manufacturing Data.* G. Marland et al, Oak Ridge National Laboratory, May 1989. ORNL/CDIAC-25. This is a useful source for data.

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*Last revised 1 May 1993 by the Information Unit on Climate Change (IUCC), UNEP, P.O. Box 356, CH-1219 Châtelaine, Switzerland. Tel. (41 22) 979 9111. Fax (41 22) 797 3464. E-mail iucc@unep.ch.*

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# The case for reducing greenhouse gas emissions despite scientific uncartainty

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**Scientific uncertainty over climate change has led some people to doubt the need for a vigorous policy response.** Although most scientists believe that human activities are changing the climate, they do not agree on the rate at which it will occur, nor on its specific impacts (fact sheets 1 and 9). This makes it difficult to put a "price tag" on either climate change or on policies to prevent it (fact sheets 228 and 229). Nevertheless, the seriousness of the potential damage and the availability of cost-effective policies are strong arguments for taking immediate action to minimize climate change.

**Action is necessary because the damage caused by climate change may be catastrophic and irreversible.** Estimates of the probable damage from climate change vary widely, from moderate to overwhelming. However, if the earth's surface warms by several degrees centigrade over the next 100 years as predicted, it seems clear that millions of people would become vulnerable to the effects of famine, drought, coastal flooding, and more. Nasty surprises, such as changes in certain ocean currents that strongly influence regional weather patterns, could not be ruled out. Once such disasters started to occur, it would take at least several generations before measures to reverse climate change could have significant results. The money spent on taking action now could be viewed as an insurance premium for protection against a hard-to-measure but potentially devastating risk.

**The first cuts in greenhouse gas emissions would be relatively cheap.** Some 10% of emissions could be eliminated by raising industrial and energy efficiency and by removing counter-productive policies, such as subsidies for clearing forests. The longer such steps are delayed, the more expensive it will become to achieve identical results with future policies. Furthermore, by the time these early reductions are completed and more expensive decisions must be made, the scientific evidence concerning climate change should be clearer.

**Reducing greenhouse gas emissions would have additional benefits unrelated to climate change.** Fuel efficiency would save money. Lower emissions of pollutants from factories and automobiles would improve air quality in urban centres and reduce acid rain. Putting a stop to deforestation would reduce soil erosion, offer aesthetic and economic benefits, and protect biodiversity and subsistence forest dwellers. One study suggested that while a hypothetical carbon tax (fact sheet 230) might cost Norway 2.75% of its GNP in the year 2010, 70% of that cost would be recouped through such non-climate benefits.1

**For further reading:**

David Pearce, et. al., "Blueprint 2: Greening the World Economy", London: Earthscan (1991).

**Notes:**

1 Glomsrod, S. et al. "Stabilization of Emissions of CO2: A Computable General Equilibrium Assessment", Central Bureau of Statistics,

Oslo (1990).

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UNEP

# Summary for Policymakers: The Science of Climate Change, IPCC Working Group I (1995)

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Considerable progress has been made in the understanding of climate change science since 1990 and new data and analyses have become available.

## Greenhouse gas concentrations have continued to increase

Increases in greenhouse gas concentrations since pre-industrial times (i.e. since about 1750) have led to a positive *radiative forcing of climate, tending to warm the surface and to produce other changes of climate.*

° *The atmospheric concentrations of greenhouse gases, inter alia* carbon dioxide (CO2), methane (CH4) and nitrous oxide (N2O) have grown significantly: by about 30%, 145%, and 15%, respectively (values for 1992). These trends can be attributed largely to human activities, mostly fossil fuel use, land-use change and agriculture.

° The growth rates of CO2, CH4 and N2O concentrations were low during the early 1990s. While this apparently natural variation is not yet fully explained, recent data indicate that the growth rates are currently comparable to those averaged over the 1980s.

° The direct radiative forcing of the long-lived greenhouse gases (2.45 Wm-2) is due primarily to increases in the concentrations of CO2 (1.56 Wm-2), CH4 (0.47 Wm-2) and N2O (0.14 Wm-2) (values for 1992).

° Many greenhouse gases remain in the atmosphere for a long time (for CO2 and N2O, many decades to centuries), hence they affect radiative forcing on long time-scales.

° The direct radiative forcing due to the CFCs and HCFCs combined is 0.25 Wm-2. However, their *net* radiative forcing is reduced by about 0.1 Wm-2 because they have caused stratospheric ozone depletion which gives rise to a negative radiative forcing.

° Growth in the concentration of CFCs, but not HCFCs, has slowed to about zero. The concentrations of both CFCs and HCFCs, and their consequent ozone depletion, are expected to decrease substantially by 2050 through implementation of the Montreal Protocol and its Adjustments and Amendments.

° At present some long-lived greenhouse gases (particularly HFCs (a CFC substitute), PFCs and SF6) contribute little to radiative forcing but their projected growth could contribute several per cent to radiative forcing during the 21st century.

°If carbon dioxide emissions were maintained at near current (1994) levels, they would lead to a nearly constant rate of increase in atmospheric concentrations for at least two centuries, reaching about 500 ppmv (approaching twice the pre-industrial concentration of 280 ppmv) by the end of the 21st century.

° A range of carbon cycle models indicates that stabilisation of atmospheric CO2 concentrations at 450, 650 or 1000 ppmv could be achieved only if global anthropogenic CO2 emissions drop to 1990 levels by, respectively, approximately 40, 140 or 240 years from now, and drop substantially below 1990 levels subsequently.

° Any eventual stabilised concentration is governed more by the accumulated anthropogenic CO2 emissions from now until the time of stabilisation, than by the way those emissions change over the period. This means that, for a given stabilised concentration value, higher emissions in early decades require lower emissions later on. Among the range of stabilisation cases studied, for stabilisation at 450, 650 or 1000 ppmv accumulated anthropogenic emissions over the period 1991 to 2100 are 630 GtC, 1030 GtC, and 1410 GtC respectively (± approximately 15% in each case). For comparison the corresponding accumulated emissions for IPCC IS92 emission scenarios range from 770 to 2190 GtC.

° Stabilisation of CH4 and N2O concentrations at today's levels would involve reductions in anthropogenic emissions of 8% and more than 50% respectively.

° There is evidence that tropospheric ozone concentrations in the Northern Hemisphere have increased since pre-industrial times because of human activity and that this has resulted in a positive radiative forcing. This forcing is not yet well characterised, but it is estimated to be about 0.4 Wm-2 (15% of that from the long-lived greenhouse gases). However the observations of the most recent decade show that the upward trend has slowed significantly or stopped.

## Anthropogenic aerosols tend to produce negative radiative forcings

° Tropospheric aerosols (microscopic airborne particles) resulting from combustion of fossil fuels, biomass burning and other sources have led to a negative direct forcing of about 0.5 Wm-2, as a global average, and possibly also to a negative indirect forcing of a similar magnitude. While the negative forcing is focused in particular regions and subcontinental areas, it can have continental to hemispheric scale effects on climate patterns.

° Locally, the aerosol forcing can be large enough to more than offset the positive forcing due to greenhouse gases.

° In contrast to the long-lived greenhouse gases, anthropogenic aerosols are very short-lived in the atmosphere, hence their radiative forcing adjusts rapidly to increases or decreases in emissions.

## Climate has changed over the past century

At any one location year-to-year variations in weather can be large, but analyses of meteorological and other data over large areas and over periods of decades or more have provided evidence for some important systematic changes.

° Global mean surface air temperature has increased by between about 0.3 and 0.6°C since the late 19th century ; the additional data available since 1990 and the re-analyses since then have not significantly changed this range of estimated increase.

° Recent years have been among the warmest since 1860, i.e., in the period of instrumental record, despite the cooling effect of the 1991 Mt. Pinatubo volcanic eruption.

° Night-time temperatures over land have generally increased more than daytime temperatures.

° Regional changes are also evident. For example, the recent warming has been greatest over the mid-latitude continents in winter and spring, with a few areas of cooling, such as the North Atlantic ocean. Precipitation has increased over land in high latitudes of the Northern Hemisphere, especially during the cold season.

° Global sea level has risen by between 10 and 25 cm over the past 100 years and much of the rise may be related to the increase in global mean temperature.

° There are inadequate data to determine whether consistent global changes in climate variability or weather extremes have occurred over the 20th Century. On regional scales there is clear evidence of changes in some extremes and climate variability indicators (e.g., fewer frosts in several widespread areas; an increase in the proportion of rainfall from extreme events over the contiguous states of the USA). Some of these changes have been toward greater variability; some have been toward lower variability.

° The 1990 to mid-1995 persistent warm-phase of the El Niño -Southern Oscillation (which causes droughts and floods in many areas) was unusual in the context of the last 120 years.

## The balance of evidence suggests a discernible human influence on global climate

Any human-induced effect on climate will be superimposed on the background "noise" of natural climate variability, which results both from internal fluctuations and from external causes such as solar variability or volcanic eruptions. Detection and attribution studies attempt to distinguish between anthropogenic and natural influences. "Detection of change" is the process of demonstrating that an observed change in climate is highly unusual in a statistical sense, but does not provide a reason for the change. "Attribution" is the process of establishing cause and effect relations, including the testing of competing hypotheses.

Since the 1990 IPCC Report, considerable progress has been made in attempts to distinguish between natural and anthropogenic influences on climate. This progress has been achieved by including effects of sulphate aerosols in addition to greenhouse gases, thus leading to more realistic estimates of human-induced radiative forcing. These have then been used in climate models to provide more complete simulations of the human-induced climate-change 'signal'. In addition, new simulations with coupled atmosphere-ocean models have provided important information about decade to century time-scale natural internal climate variability. A further major area of progress is the shift of focus from studies of global-mean changes to comparisons of modelled and observed spatial and temporal patterns of climate change.

The most important results related to the issues of detection and attribution are:

° The limited available evidence from proxy climate indicators suggests that the 20th century global mean temperature is at least as warm as any other century since at least 1400 AD. Data prior to 1400 are too sparse to allow the reliable estimation of global mean temperature.

° Assessments of the statistical significance of the observed global mean surface air temperature trend over the last century have used a variety of new estimates of natural internal and externally-forced variability. These are derived from instrumental data, palaeodata, simple and complex climate models, and statistical models fitted to observations. Most of these studies have detected a significant change and show that the observed warming trend is unlikely to be entirely natural in origin.

° More convincing recent evidence for the attribution of a human effect on climate is emerging from pattern-based studies, in which the modelled climate response to combined forcing by greenhouse gases and anthropogenic sulphate aerosols is compared with observed geographical, seasonal and vertical patterns of atmospheric temperature change. These studies show that such pattern correspondences increase with time, as one would expect as an anthropogenic signal increases in strength. Furthermore, the probability is very low that these correspondences could occur by chance as a result of natural internal variability only. The vertical patterns of change are also inconsistent with those expected for solar and volcanic forcing.

° Our ability to quantify the human influence on global climate is currently limited because the expected signal is still emerging from the noise of natural variability, and because there are uncertainties in key factors. These include the magnitude and patterns of long term natural variability and the time-evolving pattern of forcing by, and response to, changes in concentrations of greenhouse gases and aerosols, and land surface changes. Nevertheless, the balance of evidence suggests that there is a discernible human influence on global climate.

## Climate is expected to continue to change in the future

The IPCC has developed a range of scenarios, IS92a-f, of future greenhouse gas and aerosol precursor emissions based on assumptions concerning population and economic growth, land-use, technological changes, energy availability and fuel mix during the period 1990 to 2100. Through understanding of the global carbon cycle and of atmospheric chemistry, these emissions can be used to project atmospheric concentrations of greenhouse gases and aerosols and the perturbation of natural radiative forcing. Climate models can then be used to develop projections of future climate.

° The increasing realism of simulations of current and past climate by coupled atmosphere-ocean climate models has increased our confidence in their use for projection of future climate change. Important uncertainties remain, but these have been taken into account in the full range of projections of global mean temperature and sea level change.

° For the mid-range IPCC emission scenario, IS92a, assuming the "best estimate" value of climate sensitivity and including the effects of future increases in aerosol, models project an increase in global mean surface air temperature relative to 1990 of about 2°C by 2100. This estimate is approximately one third lower than the "best estimate" in 1990. This is due primarily to lower emission scenarios (particularly for CO2 and the CFCs), the inclusion of the cooling effect of sulphate aerosols, and improvements in the treatment of the carbon cycle. Combining the lowest IPCC emission scenario (IS92c) with a "low" value of climate sensitivity and including the effects of future changes in aerosol concentrations leads to a projected increase of about 1°C by 2100. The corresponding projection for the highest IPCC scenario (IS92e) combined with a "high" value of climate sensitivity gives a warming of about 3.5°C. In all cases the average rate of warming would probably be greater than any seen in the last 10,000 years, but the actual annual to decadal changes would include considerable natural variability.

Regional temperature changes could differ substantially from the global mean value. Because of the thermal inertia of the oceans, only 50-90% of the eventual equilibrium temperature change would have been realised by 2100 and temperature would continue to increase beyond 2100, even if concentrations of greenhouse gases were stabilised by that time.

° Average sea level is expected to rise as a result of thermal expansion of the oceans and melting of glaciers and ice-sheets. For the IS92a scenario, assuming the "best estimate" values of climate sensitivity and of ice melts ensitivi ty to warming, and including the effects of future changes in aerosol, models project an increase in sea level of about 50 cm from the present to 2100. This estimate is approximately 25% lower than the "best estimate" in 1990 due to the lower temperature projection, but also reflecting improvements in the climate and ice melt models. Combining the lowest emission scenario (IS92c) with the "low" climate and ice melt sensitivities and including aerosol effects gives a projected sea level rise of about 15 cm from the present to 2100. The corresponding projection for the highest emission scenario (IS92e) combined with "high" climate and ice-melt sensitivities gives a sea level rise of about 95 cm from the present to 2100. Sea level would continue to rise at a similar rate in future centuries beyond 2100, even if concentrations of greenhouse gases were stabilised by that time, and would continue to do so even beyond the time of stabilisation of global mean temperature. Regional sea level changes may differ from the global mean value owing to land movement and ocean current changes.

° Confidence is higher in the hemispheric-to-continental scale projections of coupled atmosphere-ocean climate models than in the regional projections, where confidence remains low. There is more confidence in temperature projections than hydrological changes.

° All model simulations, whether they were forced with increased concentrations of greenhouse gases and aerosols or with increased concentrations of greenhouse gases alone, show the following features: greater surface warming of the land than of the sea in winter; a maximum surface warming in high northern latitudes in winter, little surface warming over the Arctic in summer; an enhanced global mean hydrological cycle, and increased precipitation and soil moisture in high latitudes in winter. All these changes are associated with identifiable physical mechanisms.

° In addition, most simulations show a reduction in the strength of the north Atlantic thermohaline circulation and a widespread reduction in diurnal range of temperature. These features too can be explained in terms of identifiable physical mechanisms.

° The direct and indirect effects of anthropogenic aerosols have an important effect on the projections. Generally, the magnitudes of the temperature and precipitation changes are smaller when aerosol effects are represented, especially in northern mid-latitudes. Note that the cooling effect of aerosols is not a simple offset to the warming effect of greenhouse gases, but significantly affects some of the continental scale patterns of climate change, most noticeably in the summer hemisphere. For example, models that consider only the effects of greenhouse gases generally project an increase in precipitation and soil moisture in the Asian summer monsoon region, whereas models that include , in addition, some of the effects of aerosols suggest that monsoon precipitation may decrease. The spatial and temporal distribution of aerosols greatly influence regional projections, which are therefore more uncertain.

° A general warming is expected to lead to an increase in the occurrence of extremely hot days and a decrease in the occurrence of extremely cold days.

° Warmer temperatures will lead to a more vigorous hydrological cycle; this translates into prospects for more severe droughts and/or floods in some places and less severe droughts and/or floods in other places. Several models indicate an increase in precipitation intensity, suggesting a possibility for more extreme rainfall events. Knowledge is currently insufficient to say whether there will be any changes in the occurrence or geographical distribution of severe storms, e.g., tropical cyclones.

° Sustained rapid climate change could shift the competitive balance among species and even lead to forest dieback, altering the terrestrial uptake and release of carbon. The magnitude is uncertain, but could be between zero and 200 GtC over the next one to two centuries, depending on the rate of climate change.

## There are still many uncertainties

Many factors currently limit our ability to project and detect future climate change. In particular, to reduce uncertainties further work is needed on the following priority topics:

° estimation of future emissions and biogeochemical cycling (including sources and sinks) of greenhouse gases, aerosols and aerosol precursors and projections of future concentrations and radiative properties.

° representation of climate processes in models, especially feedbacks associated with clouds, oceans, sea ice and vegetation, in order to improve projections of rates and regional patterns of climate change.

° systematic collection of long-term instrumental and proxy observations of climate system variables (e.g., solar output, atmospheric energy balance components, hydrological cycles, ocean characteristics and ecosystem changes) for the purposes of model testing, assessment of temporal and regional variability and for detection and attribution studies.

Future unexpected, large and rapid climate system changes (as have occurred in the past) are, by their nature difficult to predict. This implies that future climate changes may also involve "surprises". In particular these arise from the non-linear nature of the climate system. When rapidly forced, non-linear systems are especially subject to unexpected behaviour. Progress can be made by investigating non-linear processes and sub-components of the climatic system. Examples of such non-linear behaviour include rapid circulation changes in the North Atlantic and feedbacks associated with terrestrial ecosystem changes.

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